(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
29 November 2001 (29.11.2001)

PCT

(10) International Publication Number
WO 01/91349 A2

(51) International Patent Classification[7]: H04J 14/02, G02F 1/125

(21) International Application Number: PCT/US01/15949

(22) International Filing Date: 15 May 2001 (15.05.2001)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/206,767 23 May 2000 (23.05.2000) US
09/666,210 21 September 2000 (21.09.2000) US

(63) Related by continuation (CON) or continuation-in-part (CIP) to earlier applications:
US 60/206,767 (CIP)
Filed on 23 May 2000 (23.05.2000)
US 09/666,210 (CIP)
Filed on 21 September 2000 (21.09.2000)

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(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published:
— *without international search report and to be republished upon receipt of that report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

WO 01/91349 A2

(54) **Title:** CHANNEL EQUALIZER WITH ACOUSTO-OPTIC VARIABLE ATTENUATORS

(57) **Abstract:** An optical communication assembly has an optical cross connect coupled to a first, a second, a third and a fourth set of optical fibers. A first demultiplexer is coupled to a first input fiber and the first set of optical fibers and a second demultiplexer is coupled to a second input fiber and the second set of optical fibers. A first multiplexer is coupled to a first output fiber and the third set of optical fibers. A second multiplexer is coupled to a second output fiber and the fourth set of optical fibers. A first set of attenuators is coupled to the third set of optical fibers and a second set of attenuators coupled to the fourth set of optical fibers.

CHANNEL EQUALIZER WITH ACOUSTO-OPTIC VARIABLE ATTENUATORS

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates generally to a variable optical attenuator (VOA), and more particularly to an all-fiber acousto-optic tunable intensity attenuator that is useful in optical telecommunications systems.

Description of Related Art

In modern telecommunication systems, many operations with digital signals are performed on an optical layer. For example, digital signals are optically amplified, multiplexed and demultiplexed. In long fiber transmission lines, the amplification function is performed by Erbium Doped Fiber Amplifiers (EDFA's). The amplifier is able to compensate for power loss related to signal absorption, but it is unable to correct the signal distortion caused by linear dispersion, 4-wave mixing, polarization distortion and other propagation effects, and to get rid of noise accumulation along the transmission line. For these reasons, after the cascade of multiple amplifiers the optical signal has to be regenerated every few hundred kilometers. In practice, the regeneration is performed with electronic repeaters using optical-to-electronic conversion. However to decrease system cost and improve its reliability it is desirable to develop a system and a method of regeneration, or signal refreshing, without optical to electronic conversion. An optical repeater that amplifies and reshapes an input pulse without converting the pulse into the electrical domain is disclosed, for example, in the U.S. Pat. No. 4,971,417, Radiation- Hardened Optical Repeater". The repeater comprises an optical gain device and an optical thresholding material producing the output signal when the intensity of the signal exceeds a threshold. The optical thresholding material such as polydiacetylene thereby performs a pulse shaping function.

The nonlinear parameters of polydiacetylene are still under investigation, and its ability to function in an optically thresholding device has to be confirmed.

Another function vital to the telecommunication systems currently performed electronically is signal switching. The switching function is next to be performed on the optical level, especially in the Wavelength Division Multiplexing (WDM) systems. There are two types of optical switches currently under consideration. First, there are wavelength insensitive fiber-to-fiber switches. These switches (mechanical, thermo and electro-optical etc.) are dedicated to redirect the traffic from one optical fiber to another, and will be primarily used for network restoration and reconfiguration. For these purposes, the switching time of about 1 msec (typical for most of these switches) is adequate; however the existing switches do not satisfy the requirements for low cost, reliability and low insertion loss. Second, there are wavelength sensitive switches for WDM systems. In dense WDM systems having a small channel separation, the optical switching is seen as a wavelength sensitive procedure. A small fraction of the traffic carried by specific wavelength should be dropped and added at the intermediate communication node, with the rest of the traffic redirected to different fibers without optical to electronic conversion. This functionality promises significant cost saving in the future networks. Existing wavelength sensitive optical switches are usually bulky, power- consuming and introduce significant loss related to fiber-to-chip mode conversion. Mechanical switches interrupt the traffic stream during the switching time. Acousto-optic tunable filters, made in bulk optic or integrated optic forms, (AOTFs) where the WDM channels are split off by coherent interaction of the acoustic and optical fields though fast, less than about 1 microsecond, are polarization and temperature dependent. Furthermore, the best AOTF consumes several watts of RF power, has spectral resolution about 3 nm between the adjacent channels (which is not adequate for current WDM requirements), and introduces over 5 dB loss because of fiber-to-chip mode conversions.

Another wavelength-sensitive optical switch may be implemented with a tunable Fabry Perot filter (TFPF). When the filter is aligned to a specific

wavelength, it is transparent to the incoming optical power. Though the filter mirrors are almost 100% reflective no power is reflected back from the filter . With the wavelength changed or the filter detuned (for example, by tilting the back mirror), the filter becomes almost totally reflective. With the optical circulator in front of the filter, the reflected power may be redirected from the incident port. The most advanced TFPF with mirrors built into the fiber and PZT alignment actuators have only 0.8 dB loss. The disadvantage of these filters is a need for active feedback and a reference element for frequency stability.

A VOA is in opto-mechanical device capable of producing a desired reduction in the strength of a signal transmitted through a optical fiber. Ideally, the VOA should produce a continuously variable signal attenuation while introducing a normal or suitable insertion loss and exhibiting a desired optical return loss. If the VOA causes excessive reflectance back toward the transmitter, its purpose will be defeated.

Due to the limitations of related art, there is a need for.

SUMMARY OF THE INVENTION

Accordingly, an object of the present invention is to provide a VOA in combination with an electronic feedback loop.

This and other objects of the invention are achieved in an optical communication assembly with an optical cross connect coupled to a first, a second, a third and a fourth set of optical fibers. A first demultiplexer is coupled to a first input fiber and the first set of optical fibers and a second demultiplexer is coupled to a second input fiber and the second set of optical fibers. A first multiplexer is coupled to a first output fiber and the third set of optical fibers. A second multiplexer is coupled to a second output fiber and the fourth set of optical fibers. A first set of attenuators is coupled to the third set of optical fibers and a second set of attenuators coupled to the fourth set of optical fibers.

In another embodiment of the present invention, an optical communication assembly includes a demultiplexer coupled to an input fiber, a

multiplexer coupled to an output fiber and a plurality of optical fibers. Each optical fiber is coupled to one or both of the demultiplexer and multiplexer. A plurality of attenuators are each coupled to an optical fiber. Each attenuator includes an attenuator optical fiber with a longitudinal axis, a core and a cladding in a surrounding relationship to the core. The attenuator optical fiber has a plurality of guided core modes. An acoustic wave propagation member, with a proximal end and a distal end, is included. The distal end is coupled to the attenuator optical fiber. The acoustic wave propagation member propagates an acoustic wave from the proximal to the distal end and launches an acoustic wave in the attenuator optical fiber. At least one acoustic wave generator is coupled to the proximal end of the acoustic wave propagation member.

BRIEF DESCRIPTION OF THE FIGURES

Figure 1(a) is a schematic diagram of one embodiment of an AOTF of the present invention.

Figure 1(b) is a cross-sectional view of the optical fiber of the Figure 1 AOTF.

Figure 2 is a cross-sectional view of one embodiment of an acoustic wave propagation member that can be used with the AOTF of Figure 1.

Figure 3(a) is a cross-sectional view illustrating one embodiment of an interface created between an optical fiber and a channel formed in an acoustic wave propagation member of the Figure 1 AOTF.

Figure 3(b) is a cross-sectional view illustrating an embodiment of an interface between an optical fiber and a channel formed in an acoustic wave propagation member of the Figure 1 AOTF where a bonding material is used.

Figure 4 is a schematic diagram of one embodiment of an AOTF of the present invention with an acoustic damper.

Figure 5 is a cross-sectional view of one embodiment of an index profile of an optical fiber, useful with the AOTF of Figure 1, that has a doubling cladding.

Figure 6 is a cross-sectional view of an optical fiber with sections that have different diameters.

Figure 7 is a cross-sectional view of an optical fiber with a tapered section.

Figure 8 is a perspective view of one embodiment of an AOTF of the present invention that includes a heatsink and two mounts.

Figure 9 is a perspective view of one embodiment of an AOTF of the present invention with a filter housing.

Figure 10 is a block diagram of an optical communication system with one or more AOTF's of the present invention.

Figure 11 is a schematic view showing the structure of an acousto-optic tunable filter according to one embodiment of the present invention.

Figure 12 is a graph showing the coupling and transmittance of the filter of Figure 1.

Figure 13 is a graph showing the transmittance of the filter of Figure 11.

Figure 14 is a graph showing the center wavelength of filter of Figure 1 as a function of the frequency applied to the acoustic wave generator.

Figures 15(a)-(d) are graphs illustrating the transmissions of the filter of Figure 11 when multiple frequencies are applied to the acoustic wave generator.

Figures 16(a)-(b) are graphs showing the transmittance characteristics of the filter of Figure 11 when varying an electric signal with a three frequency component applied to the filter.

Figures 17(a)-(d) are graphs for comparing the mode converting characteristic of the filter according to an embodiment of the present invention with that of a conventional wavelength filter.

Figures 18(a) illustrate one embodiment of a transmission spectrum of the Figure 11 filter.

Figure 18(b) illustrates the measured and the calculated center wavelengths of the notches as a function of acoustic frequency of an embodiment of the Figure 11 filter.

Figure 19 illustrates two examples of configurable spectral profiles with spectral tilt from the Figure 11 filter.

Figure 20(a) is a filter assembly that includes two filters of Figure 11 that are in series.

Figure 20(b) is a schematic diagram of a dual-stage EDFA with a filter of Figure 20(a).

Figure 21(a) is a graph of gain profiles of an EDFA with the filter of Figure 20(a).

Figure 21(b) is a graph illustrating filter profiles that produced the flat gain profiles shown in Figure 21(a).

Figure 21(c) is a graph illustrating filter profiles of the Figure 20(a) filter assembly.

Figures 22(a) and 22(b) are graphs illustrating the polarization dependence of one embodiment of the filter of the present invention.

Figure 23 illustrates one embodiment of the present invention from Figure 4 that has a reduction with a lower polarization dependent loss.

Figures 24(a) and 24(b) are graphs illustrating the polarization dependent loss profile of one embodiment of the invention, from Figure 4, when the filter is operated to produce 10-dB attenuation at 1550 nm.

Figure 25 illustrates an embodiment of the invention with two of the filters of Figure 1.

Figure 26 is a graph illustrating the effects of a backward acoustic reflection at the damper of one embodiment of the present invention from Figure 4.

Figure 27(a) is a graph illustrating, in one embodiment of Figure 4, the modulation depth at 10-dB attenuation level at both first- and second-harmonics of the acoustic frequency.

Figure 27(b) is a graph illustrating the modulation depth of first- and second-harmonics components from Figure 27(a).

Figure 28 is a schematic diagram of one embodiment of a VOA assembly of the present invention with a feedback loop.

Figure 29 is a schematic diagram of another embodiment of a VOA of the present invention with a demultiplexer and a multiplexer.

Figure 30 is a schematic diagram of an embodiment of a channel equalizer of the present invention using a single router.

Figure 31 is a schematic diagram of another embodiment of a channel equalizer of the present invention using multiple routers.

DETAILED DESCRIPTION

Figure 1 illustrates one embodiment of an AOTF (hereafter filter 10) of the present invention. An optical fiber 12 has a longitudinal axis, a core 14 and a cladding 16 in a surrounding relationship to core 14. Optical fiber 12 can be a birefringent or non-birefringent single mode optical fiber and a multi-mode fiber. Optical fiber 12 can have multiple cladding modes and a single core mode guided along core 14, support core to cladding modes and multiple cladding modes. Optical fiber 12 provides fundamental and cladding mode propagation along a selected length of optical fiber 12. Alternatively, optical fiber 12 is a birefringent single mode fiber that does not have multiple cladding modes and a single core mode. In one embodiment, optical fiber 12 is tensioned. Sufficient tensioning can be applied in order to reduce losses in a flexure wave propagated in optical fiber 12.

The core of optical fiber 12 is substantially circular-symmetric. The circular symmetry ensures that the refractive index of the core mode is essentially insensitive to the state of optical polarization. In contrast, in hi-birefringent single mode fibers the effective refractive index of the core mode is substantially different between two principal polarization states. The effective refractive index difference between polarization modes in high birefringence single mode fibers is generally greater than 10^{-4}. A highly elliptical core and stress-inducing members in the cladding region are two main techniques to induce large birefringence. In non-birefringent fibers, the effective index difference between polarization states is generally smaller than 10^{-5}.

An acoustic wave propagation member 18 has a distal end 20 that is coupled to optical fiber 12. Acoustic wave propagation member 18 propagates an acoustic wave from a proximal end 22 to distal end 20 and launches a flexural wave in optical fiber 12. The flexural wave creates a periodic microbend structure in the optical fiber. The periodic microbend induces an antisymmetric refractive index change in the fiber and, thereby, couples light in

the fiber from a core mode to cladding modes. For efficient mode coupling, the period of the microbending, or the acoustic wavelength, should match the beatlength between the coupled modes. The beatlength is defined by the optical wavelength divided by the effective refractive index difference between the two modes.

Acoustic wave propagation member 18 can be mechanically coupled to the optical fiber and minimizes acoustic coupling losses in between the optical fiber and the acoustic wave propagation member. In one embodiment, acoustic wave propagation member 18 is coupled to optical fiber 12 in a manner to create a lower order mode flexure wave in optical fiber 12. In another embodiment, acoustic wave propagation member 18 is coupled to the optical fiber to match a generation of modes carried by optical fiber 12.

Acoustic wave propagation member 18 can have a variety of different geometric configurations but is preferably elongated. In various embodiments, acoustic wave propagation member 18 is tapered proximal end 22 to distal end 20 and can be conical. Generally, acoustic wave propagation member 18 has a longitudinal axis that is parallel to a longitudinal axis of optical fiber 12.

At least one acoustic wave generator 24 is coupled to proximal end 22 of acoustic wave propagation member. Acoustic wave generator 24 can be a shear transducer.

Acoustic wave generator 24 produces multiple acoustic signals with individual controllable strengths and frequencies. Each of the acoustic signals can provide a coupling between the core mode and a different cladding mode. Acoustic wave generator 24 can produce multiple acoustic signals with individual controllable strengths and frequencies. Each of the acoustic signals provides a coupling between the core mode and a different cladding mode of optical fiber 12. A wavelength of an optical signal coupled to cladding 16 from core 14 is changed by varying the frequency of a signal applied the acoustic wave generator 24.

Acoustic wave generator 24 can be made at least partially of a piezoelectric material whose physical size is changed in response to an applied electric voltage. Suitable piezoelectric materials include but are not limited to

quartz, lithium niobate and PZT, a composite of lead, zinconate and titanate. Other suitable materials include but are not limited to zinc monoxide. Acoustic wave generator 24 can have a mechanical resonance at a frequency in the range of 1-20 MHz and be coupled to an RF signal generator.

Referring now to Figure 2, one embodiment of acoustic wave propagation member 18 has an interior with an optical fiber receiving channel 26. Channel 26 can be a capillary channel with an outer diameter slightly greater than the outer diameter of the fiber used and typically in the range of 80 ~ 150 microns. The length of the capillary channel is preferably in the range of 5 ~15 mm. The interior of acoustic wave propagation member 18 can be solid. Additionally, acoustic wave propagation member 18 can be a unitary structure.

Optical fiber 12 is coupled to acoustic wave propagation member 18. As illustrated in Figure 3(a), the dimensions of channel 26 and an outer diameter of optical fiber 12 are sufficiently matched to place the two in a contacting relationship at their interface. In this embodiment, the relative sizes of optical fiber 12 and channel 26 need only be substantially the same at the interface. Further, in this embodiment, the difference in the diameter of optical fiber 12 and channel 26 are in the range of 1 ~ 10 microns

In another embodiment, illustrated in Figure 3(b), a coupling member 28 is positioned between optical fiber 12 and channel 26 at the interface. Suitable coupling members 28 including but are not limited to bonding materials, epoxy, glass solder, metal solder and the like.

The interface between channel 26 and optical fiber 12 is mechanically rigid for efficient transduction of the acoustic wave from the acoustic wave propagation member 18 to the optical fiber 12.

Preferably, the interface between optical fiber 12 and channel 26 is sufficiently rigid to minimize back reflections of acoustic waves from optical fiber 12 to acoustic wave propagation member 18.

In the embodiments of Figures 3(a) and 3(b), acoustic wave propagation member 18 is a horn that delivers the vibration motion of acoustic wave generator 24 to optical fiber 12. The conical shape of acoustic wave propagation member 18, as well as its focusing effect, provides magnification of

the acoustic amplitude at distal end 20, which is a sharp tip. Acoustic wave propagation member 18 can be made from a glass capillary, such as fused silica, a cylindrical rod with a central hole, and the like.

In one embodiment, a glass capillary is machined to form a cone and a flat bottom of the cone was bonded to a PZT acoustic wave generator 24. Optical fiber 12 was bonded to channel 26. Preferably, distal end 20 of acoustic wave generator 18 is as sharp as possible to minimize reflection of acoustic waves and to maximize acoustic transmission. Additionally, the exterior surface of acoustic wave generator 18 is smooth. In another embodiment, acoustic wave generator 18 is a horn with a diameter that decreases exponentially from proximal end 22 to distal end 20.

As illustrated in Figure 4, filter 10 can also include an acoustic damper 30 that is coupled to optical fiber 12. Acoustic damper 30 includes a jacket 32 that is positioned in a surrounding relationship to optical fiber 12. Acoustic damper 30 absorbs incoming acoustic waves and minimizes reflections of the acoustic wave. The reflected acoustic wave causes an intensity modulation of the optical signal passing through the filter by generating frequency sidebands in the optical signal. The intensity modulation is a problem in most applications. A proximal end 34 of the acoustic damper 30 can be tapered. Acoustic damper 30 can be made of a variety of materials. In one embodiment, acoustic damper 30 is made of a soft material that has a low acoustic impedance so that minimizes the reflection of the acoustic wave. Jacket 32 itself is a satisfactory damper and in another embodiment jacket 32 takes the place of acoustic damper 30. Optionally, jacket 32 is removed from that portion of optical fiber 12 in a interactive region 36 and that portion of optical fiber 12 that is bonded to acoustic wave generator 24.

The interactive region is where an optical signal is coupled to cladding 16 from core 14. This coupling is changed by varying the frequency of a signal applied to acoustic wave generator 24. In one embodiment, interactive region 36 extends from distal end 20 to at least a proximal portion within acoustic damper 30. In another embodiment, interactive region 36 extends from distal end 20 and terminates at a proximal end of acoustic damper 30. In one

embodiment, the length of optical fiber 12 in interactive region is less than 1 meter, and preferably less than 20 cm. The nonuniformity of the fiber reduces the coupling efficiency and also causes large spectral sidebands in the transmission spectrum of the filter. Another problem of the long length is due to the mode instability. Both the polarization states of the core and cladding modes and the orientation of the symmetry axis of an antisymmetric cladding mode are not preserved as the light propagates over a long length greater than 1 m. This modal instability also reduces the coupling efficiency and causes large spectral sidebands. Preferably, the outer diameter of optical fiber 12, with jacket 32, is in the range of 60-150 microns.

The profile of the refractive index of the cross section of optical fiber 12 influences its filtering characteristics. One embodiment of optical fiber 12, illustrated in Figure 5, has a first and second cladding 16' and 16" with core 14 that has the highest refractive index at the center. First cladding 16' has an intermediate index and second cladding 16" has the lowest index. Most of the optical energy of several lowest-order cladding modes is confined both only in core 14 and first cladding 16'. The optical energy falls exponentially from the boundary between first and second claddings 16' and 16", respectively.

Optical fields are negligible at the interface between second cladding 16" and the surrounding air, the birefringence in the cladding modes, due to polarization-induced charges, is much smaller than in conventional step-index fibers where second cladding 16" does not exist. The outer diameter of first cladding 16' is preferably smaller than that of second cladding 16", and can be smaller by at least 5 microns. In one specific embodiment, core 14 is 8.5 microns, first cladding 16' has an outer diameter of 100 microns and second cladding 16" has an outer diameter of 125 microns. Preferably, the index difference between core 14 and first cladding 16' is about 0.45%, and the index difference between first and second claddings 16' and 16" is about 0.45%.

In another embodiment, the outer diameter of first cladding 16' is sufficiently small so that only one or a few cladding modes can be confined in first cladding 16'. One specific example of such an optical fiber 12 has a core 14 diameter of 4.5 microns, first cladding 16' of 10 microns and second

cladding 16" of 80 microns, with the index difference between steps of about 0.45% each.

The optical and acoustic properties of optical fiber 12 can be changed by a variety of different methods including but not limited to, (i) fiber tapering, (ii) ultraviolet light exposure, (iii) thermal stress annealing and (iv) fiber etching.

One method of tapering optical fiber 12 is achieved by heating and pulling it. A illustration of tapered optical fiber 12 is illustrated in Figure 6. As shown, a uniform section 38 of narrower diameter is created and can be prepared by a variety of methods including but not limited to use of a traveling torch. Propagation constants of optical modes can be greatly changed by the diameter change of optical fiber 12. The pulling process changes the diameter of core 14 and cladding 16 and also changes the relative core 14 size due to dopant diffusion. Additionally, the internal stress distribution is modified by stress annealing. Tapering optical fiber 12 also changes the acoustic velocity.

When certain doping materials of optical fiber 12 are exposed to ultraviolet light their refractive indices are changed. In one embodiment, Ge is used as a doping material in core 14 to increase the index higher than a pure SiO_2 cladding 16. When a Ge-doped optical fiber 12 is exposed to ultraviolet light the index of core 14 can be changed as much as 0.1%. This process also modifies the internal stress field and in turn modifies the refractive index profile depending on the optical polarization state. As a result, the birefringence is changed and the amount of changes depends on optical modes. This results in changes of not only the filtered wavelength at a given acoustic frequency or vice versa but also the polarization dependence of the filter. Therefore, the UV exposure can be an effective way of trimming the operating acoustic frequency for a given filtering wavelength as well as the polarization dependence that should preferably be as small as possible in most applications.

Optical fiber 12 can be heated to a temperature of 800 to 1,300 °C or higher to change the internal stresses inside optical fiber 12. This results in modification of the refractive index profile. The heat treatment is another way of controlling the operating acoustic frequency for a given filtering wavelength as well as the polarization dependence.

The propagation velocity of the acoustic wave can be changed by chemically etching cladding 16 of optical fiber 12. In this case, the size of core 14 remains constant unless cladding is completely etched. Therefore, the optical property of core mode largely remains the same, however, that of a cladding mode is altered by a different cladding diameter. Appropriate etchants include but are not limited to hydro fluoride (HF) acid and BOE.

The phase matching of optical fiber 12 can be chirped. As illustrated in Figure 6, a section 40 of optical fiber can have an outer diameter that changes along its longitudinal length. With section 40, both the phase matching condition and the coupling strength are varied along its z-axis 42 and the phase matching conditions for different wavelengths satisfied at different positions along the axis. The coupling then can take place over a wide wavelength range. By controlling the outer diameter as a function of its longitudinal axis 42, one can design various transmission spectrum of the filter. For example, uniform attenuation over a broad wavelength range is possible by an appropriate diameter control.

Chirping can also be achieved when the refractive index of core 14 is gradually changed along z-axis 42. In one embodiment, the refractive index of core 14 is changed by exposing core 14 to ultraviolet light with an exposure time or intensity as a function of position along the longitudinal axis. As a result, the phase matching condition is varied along z-axis 42. Therefore, various shapes of transmission spectrum of the filter can be obtained by controlling the variation of the refractive index as a function of the longitudinal axis 42.

As illustrated in Figure 8 a heatsink 44 can be included to cool acoustic wave generator. In one embodiment, heatsink 44 has a proximal face 46 and a distal face 48 that is coupled to the acoustic wave generator 24. Preferably, acoustic wave generator 24 is bonded to distal face 48 by using a low-temperature-melting metal-alloy solder including but not limited to a combination of 95% zinc and 5% tin and indium-based solder materials. Other bonding material includes heat curable silver epoxy. The bonding material should preferably provide good heat and electrical conduction. Heatsink 44

provides a mount for the acoustic wave generator 24. Heatsink can be made of a variety of materials including but not limited to aluminum, but preferably is made of a material with a high heat conductivity and a low acoustic impedance.

Acoustic reflections at proximal face can be advantageous if controlled. By introducing some amount of reflection, and choosing a right thickness of heatsink 44, the RF response spectrum of acoustic wave generator 24 can be modified so the overall launching efficiency of the acoustic wave in optical fiber can be less dependent on the RF frequency.

In this case, the reflectivity and size of heatsink 44 is selected to provide a launching efficiency of the flexural wave into optical fiber 12 almost independent of an RF frequency applied to acoustic wave generator 24. The thickness of heatsink 44 is selected to provide a travel time of an acoustic wave from distal face 48 to proximal face 46, and from proximal face 46 to distal face 48 that substantially matches a travel time of the acoustic wave traveling through acoustic wave propagation member 24 from its proximal end to its distal end, and from its distal end to its proximal end. The heat sink material or the material for the attachment to the proximal face 46 is selected to provide the amount of back reflection from the heat sink that substantially matches the amount of back reflection from the acoustic wave propagation member. In various embodiments, the proximal and distal faces, 46, 48 of heatsink 44 have either rectangular or circular shapes with the following dimensions: 10x10 mm^2 for the rectangular shape and diameter of 10 mm for the cylindrical shaped heat sink.

However, acoustic back reflections due to proximal face 46 are preferably avoided. Acoustic reflections from the heat sink back to the acoustic wave generator are reduced by angling proximal face 46 at an angle greater than 45 degree or by roughing the face. The acoustic wave coming from the acoustic generator toward the angled proximal face 46 is reflected away from the acoustic generator, reducing the acoustic back reflection to the acoustic wave generator. The roughed face also reduces the acoustic reflection by scattering the acoustic wave to random directions. Preferably, the side faces of the heat sink are also roughened or grooved to scatter the acoustic wave and thereby to

avoid the acoustic back reflection. Another method to reduce the back reflection is to attach an acoustic damping material at the proximal face 46. Suitable materials that reduce back reflections include soft polymers, silicone, and the like that can be applied to proximal face 46.

Referring again to Figure 8, an acoustic damper mount 50 supports acoustic damper 30. Acoustic damper mount 50 can be made of a variety of materials including but not limited to silica, invar, and the like. A filter mount 52 supports heatsink 44 and acoustic damper mount 50. In one embodiment, filter mount is a plate-like structure. Preferably, filter mount 52 and optical fiber 12 have substantially the same thermal expansion coefficients. Filter mount 52 and fiber 12 can be made of the same materials.

Filter mount 52 and optical fiber 12 can have different thermal expansion coefficients and be made of different materials. In one embodiment, filter mount 52 has a lower thermal expansion coefficient than optical fiber 12. Optical fiber 12 is tensioned when mounted and bonded to the filter mount 52. The initial strain on optical fiber 12 is released when the temperate increases because the length of filter mount 52 is increased less than optical fiber 12. On the other hand, when the temperature decreases optical fiber 12 is stretched further. When the amount of strain change according to temperature change is appropriately chosen by selecting proper material for mount the 52, the filtering wavelength of filter 10 can be made almost independent of temperature. Without such mounting arrangement, the center wavelength of the filter increases with temperature. Additionally, interactive region 36 of is sufficiently tensioned to compensate for changes in temperature of the interactive region 36 and filter mount 52.

In another embodiment, illustrated in Figure 9, a filter housing 54 encloses interactive region 36. Filter housing 54 can be made of a variety of materials, including but not limited to silica, invar and the like. Filter housing 54 eliminates the need for a separate filter mount 52. Filter housing 54 extends from distal face 48 of heatsink 44 to acoustic damper 30 or to a jacketed portion 32 of optical fiber 12. Acoustic wave propagation member 18, acoustic wave

generator 24 and the acoustic damper 30 can be totally or at least partially positioned in an interior of filter housing 54.

In one embodiment, filter housing 54 and optical fiber 12 are made of materials with substantially similar thermal expansion coefficients. A suitable material is silica. Other materials are also suitable and include invar. Filter housing 54 and optical fiber 12 can have different thermal expansion coefficients and be made of different materials. In one embodiment, filter housing 54 has a lower thermal expansion coefficient than optical fiber 12.

In one embodiment, interactive region 36 is sufficiently tensioned sufficiently to compensate for changes in temperature of interactive region 36 and filter housing 54.

As illustrated in Figure 10, filter 10 can be a component or subassembly of an optical communication system 56 that includes a transmitter 58 and a receiver 60. Transmission 58 can include a power amplifier with filter 10 and receiver 60 can also include a pre amplifier that includes filter 10. Additionally, optical communication system 56 may also have one or more line amplifiers that include filters 10.

Referring now to Figure 11, if an electric signal 57 with constant frequency "f" is applied to acoustic wave generator 24, a flexural acoustic wave having the same frequency "f" is generated. The flexural acoustic wave is transferred to optical fiber 12 and propagates along optical fiber 12, finally absorbed in acoustic damper 30. The flexural acoustic wave propagating along optical fiber 12 produces periodic microbending along the fiber, resulting in the periodic change of effective refractive index which the optical wave propagating along optical fiber 12 experiences. The signal light propagating along optical fiber 12 in a core mode can be converted to a cladding mode by the change of effective refractive index in optical fiber 12.

When signal light is introduced into filter 10 part of the signal light is converted to a cladding mode due to the effect of the acoustic wave and the remainder of the signal light propagates as a core mode while the signal light propagates along interactive region 36. The signal light converted to a cladding mode cannot propagate any longer in optical fiber 12 with jacket 32 because the

light is partly absorbed in optical fiber 12 or partly leaks from optical fiber 12. A variety of mode selecting means, including a mode conversion means between core modes and cladding modes, can be incorporated in filter 10. For example, the long-period grating described in the article "Long-period fiber-grating based gain equalizers" by A. M. Vengsarkar et al. in Optics Letters, Vol. 21, No. 5, p. 336, 1996 can be used as the mode selecting means. As another example, a mode coupler, which converts one or more cladding modes of one fiber to core modes of the same fiber or another fiber, can also be used.

A flexural acoustic wave generated by acoustic wave propagation member 18 propagates along interactive region 36. The acoustic wave creates antisymmetric microbends that travel along interactive region 36, introducing a periodic refractive-index perturbation along optical fiber 12. The perturbation produces coupling of an input symmetric fundamental mode to an antisymmetric cladding mode when the phase-matching condition is satisfied in that the acoustic wavelength is the same as the beat length between the two modes. The coupled light in the cladding mode is attenuated in jacket 32. For a given acoustic frequency, the coupling between the fundamental mode and one of the cladding modes takes place for a particular optical wavelength, because the beat length has considerable wavelength dispersion. Therefore, filter 10 can be operated as an optical notch filter. A center wavelength and the rejection efficiency are tunable by adjustment of the frequency and the voltage of RF signal applied to acoustic wave propagation member 18, respectively.

The coupling amount converted to a cladding mode is dependent on the wavelength of the input signal light. Figure 12(a) shows the coupling amounts as functions of wavelength when flexural acoustic waves at the same frequency but with different amplitudes are induced in optical fiber 12. As shown in Figure 12(a), the coupling amounts are symmetrical with same specific wavelength line (λ_c), i.e.,. center wavelength line, however they show different results 62 and 64 due to the amplitude difference of the flexural acoustic waves. Therefore, the transmittance of the output light which has passed through filter 12 is different depending on the wavelength of the input light. Filter 12 can act

as a notch filter which filters out input light with specific wavelength as shown in Figure 12(b).

Figure 12(b) is a graph showing the transmittances as a function of wavelength when flexural acoustic waves with different amplitudes are induced in optical fiber 12. The respective transmittances have same center wavelength as does the coupling amount, but different transmittance characteristic 64 and 66 depending on the amplitude difference of the flexural acoustic waves can be shown.

The center wavelength λ_c, of filter 10 satisfies the following equation.

$$\beta_{co}(\lambda) - \beta_{cl}(\lambda) = 2\pi/\lambda_a$$

In the above equation, $\beta_{co}(\lambda)$ and $\beta_{cl}(\lambda)$ are propagation constants of core mode and cladding mode in optical fiber 12 which are respectively dependent on the wavelength, and λ_a represents the wavelength of the flexural acoustic waves.

Accordingly, if the frequency of the electric signal applied to acoustic wave generator 24 varies, the wavelength of the acoustic wave generated in optical fiber 12 also varies, which results in the center wavelength change of filter 10. In addition, since the transmission is dependent on the amplitude of the flexural acoustic wave, the transmission of signal light can be adjusted by varying the amplitude of the electric signal which is applied to acoustic wave generator 24.

Figure 13 is a graph showing the transmittance of filter 10 in one embodiment when different electric signal frequencies are applied. As shown in Figure 13, each center wavelength (i.e., wavelength showing maximum attenuation) of filter 10 for different electric signals was 1530nm, 1550nm and 1570nm. Therefore the center wavelength of filter 10, according to the embodiment, is changed by varying the frequency of the electric signal which is applied to acoustic wave generator 24.

As described above, since there are a plurality of cladding modes in interactive region 36 the core mode can be coupled to several cladding modes. Figure 14 is a graph showing the center wavelength of filter 10 according to the embodiment of the invention as a function of the frequency applied to the

flexural acoustic wave generator. In Figure 14, straight lines 71, 72 and 73 represent the center wavelength of filter 10 resulting from the coupling of a core mode with three different cladding modes.

Referring to Figure 14, there are three applied frequencies for any one optical wavelength in this case. Therefore the input signal light is converted to a plurality of cladding modes by applying multi-frequency electric signal to acoustic wave generator 24. Moreover, it means transmission characteristics of filter 10 can be electrically controlled by adjusting the amplitude and each frequency component of the electric signal.

As shown in Figure 15(a), the respective transmission features 74, 75 and 76 of filter 10 can be provided by applied electric signals with different frequencies fl, f2 and f3. In this example, assuming that fl couples the core mode of input signal light to a cladding mode (cladding mode A), f2 couples the core mode to other cladding mode (cladding mode B) and f3 couples the core mode to another cladding mode different from A or B (cladding mode C, the transmission feature is shown in Figure 15(b) as a curve 77 when electric signal with three frequency components fl, f2 and S is applied to acoustic wave generator 24.

As shown in Figure 15(c), if filter 10 has transmission feature curves 78, 79 and 80 corresponding to respective frequencies fl', f2' and f3' and electric signal having three frequency components fl', f2' and f3' is applied to the flexural acoustic wave generator, the transmission feature of filter 10 is shown as a curve 81 of Figure 15(d).

Figures 16(a) and 16(b) are graphs showing the transmittance of filter 10 according to an embodiment of the present invention, when varying electric signal having three frequency components is applied to filter 10. When varying electric signal having a plurality of frequency components is applied to acoustic wave generator 24 various shapes of transmittance curves 82, 83 and 84 can be obtained.

Since conventional tunable wavelength filters utilize the coupling of only two modes, the difference between a plurality of applied frequencies naturally becomes small to obtain wide wavelength band filtering feature by

applying a plurality of frequencies. In this case, as described under the article "Interchannel Interference in multiwavelength operation of integrated acousto-optical filters and switches" by F. Tian and H. Herman in Journal of Light wave technology 1995, Vol. 13, n 6, pp. 1146-1154, when signal light input to a filter is simultaneously converted into same (polarization) mode by various applied frequency components, the output signal light may undesirably be modulated with frequency corresponding to the difference between the applied frequency components. However, with filter 10 the above problem can be circumvented, because the respective frequency components convert the mode of input light into different cladding modes in filter 10.

In one embodiment, the filtering feature shown in Figure 17(a) was obtained by applying adjacent frequencies 2.239MHz and 2.220MHz to reproduce the result of a conventional method. The applied two frequencies were such that convert the mode of input light into the same cladding mode. Under the condition, narrow wavelength-band signal light with a center wavelength of 1547 nm was input to filter 10 to measure output light. Referring to the measurement result shown in Figure 17(b), there is an undesirable modulated signal with frequency corresponding to the difference of the two applied frequencies.

In another embodiment, when adjacent frequencies 2.239 MHz and 2.220 MHz were applied to acoustic wave generator 24, according to the embodiment of the invention, the two frequency components convert the mode of input light into mutually different cladding modes. Figure 17(c) shows the measurement result when the same signal light as the above experiment was input to filter 10 and output light was measured.

However, an undesirable modulated signal, which appeared in a conventional filter, practically disappeared as shown in Figure 17(d).

In optical communications or optical fiber sensor systems, wavelength filters are required that has a wide tuning range and are capable of electrically controlling its filtering feature.

Figure 18(a) illustrates one embodiment of a transmission spectrum of filter 10 with a 15.5-cm-long interaction length for a broadband unpolarized

input light from a LED. A conventional communication fiber was used with a nominal core diameter of 8.5 μm, a cladding outer diameter of 125 μm and a normalized index difference of 0.37%. The frequency of the applied RF signal was 2.33 MHz, and the corresponding acoustic wavelength was estimated to be ~650 μm. The three notches shown in Figure 8(a) are from the coupling to three different cladding modes with the same beat length at the corresponding wavelengths. The coupled cladding modes were the $LP_{11}^{(cl)}$, the $LP_{12}^{(cl)}$, and the $LP_{13}^{(cl)}$ modes, which was confirmed from far-field radiation patterns. The center of each coupling wavelength was tunable over > 100 nm by tuning the acoustic frequency.

Figure 18(b) shows the measured and the calculated center wavelengths of the notches as a function of acoustic frequency. The fiber parameters used in the calculation for best fit with the experimental results are a core diameter of 8.82 μm, a cladding outer diameter of 125 μm, and a normalized index difference of 0.324%, in reasonable agreement with the experimental fiber parameters.

Referring again to Figure 8(a), coupling light of a given wavelength from the fundamental mode to different cladding modes requires acoustic frequencies that are separated from each other by a few hundred kilohertz. This separation is large enough to provide a wide wavelength-tuning range of almost 50 nm for each coupling mode pair without significant overlap with each other, thereby practically eliminating the coherent cross talk that is present in conventional counterparts. The tuning range is sufficient to cover the bandwidth of typical EDFA's. In one embodiment, filter 10 provides for a combination of independent tunable notch filters built into one device, and the number of involved cladding modes corresponds to the number of filters. The multifrequency acoustic signals can be generated by a single transducer, and the spectral profile of filter 10 is determined by the frequencies and amplitudes of the multiple acoustic signals.

Figure 19 shows two examples of the configurable spectral profiles with spectral tilt, which can be used to recover the gain flatness in an EDFA with a gain tilt caused by signal saturation. In one embodiment, three cladding modes

[$LP_{11}^{(cl)}$, the $LP_{12}^{(cl)}$, and the $LP_{13}^{(cl)}$] were used and three RF signals were simultaneously applied with different voltages and frequencies adjusted for the particular profile. The 3-dB bandwidth of the individual notch was ~6 nm with a 10-cm-long interaction length.

A complex filter profile is required to flatten an uneven EDFA gain, which exhibits large peaks with different widths around 1530 and 1560 nm. The combination of three Gaussian shaped passive filters can produce a flat gain over a 30-nm wavelength range.

As illustrated in Figure 20(a), a filter assembly of the present invention can include first and second filters 10' and 10" in series. Each filter 10' and 10" is driven by three radio frequency (RF) signals at different frequencies and amplitudes that produce acousto-optic mode conversion from the fundamental mode to different cladding modes. This approach eliminates the detrimental coherent crosstalk present in $LiNbO_3$-based AOTF's. The 3-dB bandwidths of the first filter 10' were 3.3, 4.1, and 4.9 nm for the couplings to the cladding modes $LP_{12}^{(cl)}$, the $LP_{13}^{(cl)}$, and $LP_{14}^{(cl)}$, respectively. For second filter 10", they were 8, 8.6, and 14.5 nm for the couplings to the cladding modes, $LP_{11}^{(cl)}$, the $LP_{12}^{(cl)}$, and the $LP_{13}^{(cl)}$ respectively.

The minimum separations of notches produced by single RF driving frequency were ~50 nm for first filter 10' and ~150 nm for second filter 10", respectively, so that only one notch for each driving frequency falls into the gain-flattening range (35 nm). The large difference between filters 10' and 10" was due to the difference in optical fiber 12 outer diameters. The polarization splitting in the center wavelength of the notches as ~0.2 nm for first filter 10' and ~1.5 nm for second filter 10". The relatively large polarization dependence in second filter 10" is due mainly due to the unwanted core elliptically and residual thermal stress in optical fiber 12, that can be reduced to a negligible level by using a proper optical fiber. First and second filters 10' and 10" were used for the control of the EDFA gain shape around the wavelengths of 1530 and 1555 nm, respectively. The background loss of the gain flattening AOTF was less than 0.5 dB, which was mainly due to splicing of different single-mode

fibers used in the two AOTF's 1010. Adjusting the frequencies and voltages of the applied RF signals provided control of the positions and depths of the notches with great flexibility. The RF's were in the range between 1 and 3 MHz.

Figure 20(b) shows a schematic of a dual-stage EDFA employing gain flattening filter 10 along with a test setup. A 10-m-long EDF pumped by a 980-nm laser diode and a 24-m-long EDF pumped by a 1480-nm laser diode were used as the first and the second stage amplifiers, respectively. The peak absorption coefficients of both EDF's were ~2.5 dB/m at 1530 nm. Filter 10 was inserted between the two stages along with an isolator. Total insertion loss of filter 10 and the isolator was less than 0.9 dB. Six synthesizers and two RF power amplifiers were used to drive filter 10.

Gain profiles of the EDFA were measured using a saturating signal at the wavelength of 1547.4 nm and a broad-band light-emitting diode (LED) probing signal. The saturating signal from a distributed feedback (DFB) laser diode was launched into the EDFA after passing through a Fabry-Perot filter (optical bandwidth: 3 GHz, extinction ratio: 27 dB) to suppress the sidelobes of the laser diode. The total power of the probe signal in 1520-1570-nm range was 27 dBm, which is much smaller than that of the input saturating signal ranging from 13 to 7 dBm.

Figure 21(a) shows gain profiles before and after the gain flattening for two different saturating signal powers of 13 and 7 dBm when the second-stage pump power was 42 mW. The gain excursions before flattening were larger than 5 dB. By adjusting the filter profile, flat gain profiles within 0.7 dB were obtained over 35 nm for both cases. The flat gain region is shifted slightly toward the shorter wavelength for higher gain level, which is due to the intrinsic gain characteristics of the EDF. Figure 21(b) shows filter profiles that produced the flat gain profiles shown in Figure 21(a), where Profile 1 and Profile 2 are for the cases of saturating tones of 13 and 7 dBm, respectively. For the measurements, EDFI was used as an ASE source, while the second pump diode (1480 nm) was turned off. The ASE signal leaked out of the second WDM coupler was monitored and the signals obtained when the filter was on and off

were compared to yield the filter response. The attenuation coefficients for Profile 1 and Profile 2 at the saturating signal wavelength were 5.0 and 4.9 dB, respectively, and the average attenuation over the 35-nm range (1528-1563 nm) was 5 dB in both cases. The total RF electrical power consumption of the filter was less than 500 mW. Profile 2 could be obtained from Profile 1 by adjusting mainly the depths of notches, although fine adjustments of center wavelengths of notches within 0.5-nm range slightly improved the gain flatness. Figure 21(c) shows the filter profiles of first filter 10' and second filter 10" used to form Profile 1, and also the locations of center wavelengths of six notches. By adjusting first and second filters 10' and 10" spectral profiles electronically gain flatness of <0.7 dB over 35-nm wavelength range were obtained at various levels of gain as well as input signal and pump power.

One important characteristic of filter 10 is polarization dependence. The shape of filter 10 can be dependent on the polarization state of input light. The polarization dependence originates from fiber birefringence. Fiber birefringence causes the effective propagation constant of a mode to be different between two eigen polarization states. Since the magnitude of birefringence is different from mode to mode, the fiber birefringence causes the beat length between two coupled modes to be different between the eigen polarization states, and, therefore, results in splitting of center wavelength of filter 10 for a given acoustic frequency.

Figure 22(a) illustrates the polarization dependence. Curve 90 represents the filter profile for light in one eigen polarization state, and filter profile 92 is when the input is in the other eigen state. The center wavelengths are split because of the birefringence. Moreover, since the field overlap between two coupled modes is also polarization dependent due to the birefringence, the attenuation depth can be different between filter profiles 90 and 92.

A critical feature due to the polarization dependence is the polarization dependent loss (PDL) which is defined as the difference of the magnitude of attenuation between two eigen polarization states. Since polarization dependent loss is an absolute value, it increases with the attenuation depth. Figure 22(b) shows polarization dependent loss profile 93 associated with filter profiles 90

and 92. In WDM communication system applications, the polarization dependent loss should be minimized. Most applications require the polarization dependent loss to be less than 0.1 dB. However, acousto-optic tunable filter 10 has exhibited a typical polarization dependent loss as large as 2 dB at 10-dB attenuation level. This is due to the large birefringence of the antisymmetric cladding modes.

Figure 23 shows one possible configuration that can reduce the inherent polarization dependent loss of filter 10. In Figure 23, double-pass filter 100 consists of a 3-port circulator with input-, middle-, and output-port fibers, 12', 12'' and 12''', respectively, and Faraday rotating mirror (FRM) 104. The middle-port fiber 12'' is connected to acousto-optic tunable filter 10 and Faraday rotating mirror 104. When light comes in through input-port fiber 12', it is directed to filter 10, through circulator 102, and then refracted by Faraday rotating mirror 104. Faraday rotating mirror 104 acts as a conjugate mirror with respect to optical polarization states. So, if the light pass through filter 10 in a specific polarization state, then on the way back after reflection it pass through filter 10 in its orthogonal polarization state. Since the light pass through filter 10 twice but in mutually orthogonal states, the total attenuation after the double pass becomes polarization-insensitive. Another benefit of the double pass configuration is that, since the filtering takes place twice in filter 10, the drive RF power applied to filter 10 to obtain a certain attenuation depth is reduced half compared to single-pass configuration as in Figure 4. For instance, when filter 10 is operated at an attenuation depth of 5 dB, the overall attenuation depth of double-pass filter 100 becomes 10 dB.

Another embodiment of a device configuration for low polarization dependence is shown in Figure 24. In this embodiment, dual filter 110 consists of filters 10' and 10'' in tandem and connected through mid fiber section 112. Filters 10' and 10'' are preferably operated at the same RF frequency. The birefringence of mid fiber section 112 is adjusted such that it acts as a half-wave plate aligned with 45-degree angle with respect to the eigen polarization axes of filters 10' and 10''. In other words, the light passing through filter 10' in one eigen polarization state enters filter 10'' in the other eigen polarization state. If

the polarization dependent loss is the same loss for filters 10' and 10'', the overall attenuation after passing through filters 10' and 10'' becomes polarization-insensitive. If filters 10' and 10'' are not identical in terms of polarization dependent loss, the double filter 110 would exhibit residual polarization dependent loss that should be, however, smaller than the polarization dependent loss of individual filters, 10' or 10''. Therefore, it is desirable that filters 10' and 10'' are identical devices. Since the filtering takes place by two filters, the drive powers to individual filters are reduced, compared to using a single filter alone, to achieve the same attenuation depth.

In one embodiment, illustrated in Figure 23, circulator 102 based on magneto-optic crystal has overall insertion loss and polarization dependent loss of 1.5 dB and 0.5 dB, respectively. Faraday rotating mirror 104 has insertion loss and polarization dependent loss of 0.5 dB and 0.5 dB, respectively. Curve 120 in Figure 24(a) shows the polarization dependent loss profile in one embodiment when filter 10 was operated to produce 10-dB attenuation at 1550 nm. The filter profile in this instance is shown by curve 124 in Figure 24(b). Optical fiber 12 used in the filter was a conventional communication-grade single mode fiber. When the filter was used in the double-pass configuration, the overall polarization dependent loss was reduced greatly as shown by curve 121 in Figure 24(a).

The polarization dependent loss was reduced down to less than 0.2 dB. The total insertion loss of double-pass filter was 3 dB, mainly due to the circulator and splices. In this embodiment, the drive power to filter 10 required to produce total 10-dB attenuation at 1550 nm, as shown by filter profile 125 in Figure 24(b), was decreased compared to the single-pass filter experiment.

In another embodiment, illustrated in Figure 25, two filters were fabricated with a conventional circular-core single mode fiber. Each filter was operated with 5-dB attenuation at the same center wavelength, 1550 nm. The overall dual filter profile is shown by curve 126 in Figure 24(b). In these filters, the eigen polarization states are linear and their axes are parallel and orthogonal to the direction of the flexural acoustic wave vibration or the acoustic polarization axis. This is generally true with filters made of a circular-core fiber

where the dominant birefringence axes are determined by the lobe orientation of the cladding mode, which is the same as the acoustic polarization axis. Linear axis orthogonal to acoustic polarization is the slow axis, and its orthogonal axis is the fast axis. In this embodiment, a polarization controller was used in mid fiber section 112 and controlled to minimize the overall polarization dependent loss of dual filter 110.

The loss profile is shown by curve 122 in Figure 24(a). The total filter profile is shown by curve 126 in Figure 24(b). The residual polarization dependent loss as large as 0.6 dB is primarily due to different polarization dependent loss of filters 10' and 10'', and could be reduced greatly if identical two filters were used.

Another important characteristic of filter 10 is the intensity modulation of an optical signal passing through the filter. One reason which gives rise to the intensity modulation of the output signal is static coupling between the core and cladding modes either by microbending of fiber 12 or imperfect splices, if present. Another reason is an acoustic wave propagating backward in interactive region 36 by an acoustic reflection at imperfect acoustic damper 30 and fiber jacket 32. Figure 26 shows an example of output signal 139 suffering from the intensity modulation by backward acoustic reflection at acoustic damper 30. In this case, the major modulation frequency is equal to twice the acoustic frequency. The modulation depth is defined by the ratio of peak-to-peak AC voltage amplitude, V_{AC} to DC voltage, V_{DC}. By static mode coupling, the major modulation frequency is equal to the acoustic frequency. When both static mode coupling and backward acoustic wave are present, the intensity of the output is modulated at frequencies of both first- and second-harmonics of the acoustic frequency. The modulation depth, when smaller than 20%, is, approximately, linearly proportional to the amount of attenuation in dB scale. In most WDM communication system applications, the modulation depth is generally required to be less than 3% at 10-dB attenuation level.

In one embodiment, illustrated in Figure 4, filter 10 was fabricated by using a conventional single-mode fiber. The modulation depth at 10-dB attenuation level was about 10% at both first- and second-harmonics of the

acoustic frequency, as shown by curves 140 and 141 in Figure 27(a), respectively. The same filter was used as filter 10 in another embodiment, illustrated in Figure 23. The RF drive power to the filter was controlled to produce 10-dB attenuation depth. In the first embodiment of double-pass filter 100, the length of fiber section 106 was selected such that the round-trip travel time of fiber section 106 is equal to a quarter of the period of the acoustic wave. In this case, the second-harmonics component of the intensity modulation can be compensated out. Curves 142 and 143 in Figure 27(a) show the modulation depth of first- and second-harmonics components, respectively. The second-harmonics was eliminated almost completely. The first-harmonics was also reduced a little, which may be attributed to imperfect length matching of fiber section 106. In the second embodiment of double-pass filter 100, the length of fiber section 106 was such that the optical round-trip travel time of fiber section 106 is equal to a half of the period of the acoustic wave. In this case, the first-harmonics component of the intensity modulation can be reduced. Curves 147 and 148 in Figure 27(b) show the modulation depth of first- and second-harmonics components, respectively. The first-harmonics was eliminated almost completely.

Reduction of intensity modulation can also be achieved by dual filter 110 where the length of mid fiber section 112 is selected properly. For example, if the first-harmonic modulation component is to be compensated, the length of mid fiber section 112 is such that the optical travel time from one end of section 112 to the other end is equal to a half of the period of the acoustic wave.

Referring now to Figure 28, one embodiment of the present invention is a tunable VOA assembly 150 that includes a tunable VOA 152, coupled to a tap coupler 154, a detector 156 and an attenuator control circuit 158 that creates a local loop. A network loop is created by coupling attenuator control circuit 158 to network components in order to receive network commands. Attenuator 152 can be a liquid crystal attenuator, a MEMS device, an acoustic-optic device, a Fabry Perot device, a mechanical sliding attenuator, a magneto-optic device and the like.

Tap coupler 154 can be a fused directional coupler, a bulk optic filter, a grating positioned in a fiber, and the like. Detector 156 can be any photodetector well known to those skilled in the art.

In a preferred embodiment, VOA 152 couples light from a fundamental core mode of an optical fiber to a higher-order mode such as a higher order core mode or a cladding mode. The configuration of VOA 152 is preferably the same as AOTF 10. The amount of coupling is determined by the amplitude of the acoustic wave. Transmission in the fundamental core mode is controlled by the voltage of an RF signal applied to the transducer.

Optical tap coupler 154, optical power detector 156 , and an attenuator control circuit 158 provide a feedback loop to VOA 152. Additionally, the feedback signal can come from other system elements, not shown, that are coupled with VOA system 150. Control circuit 158 can include a decision circuit and an RF generator. Control circuit 158 compares the output signal power determined from the detector output with a target value required by a system operator. Control circuit 158 controls the voltage of the RF signal that goes to the transducer of VOA 152 so that the optical signal power approaches the target value.

VOA assembly 150 is suitable with single or multiple wavelength channels and/or bands, depending on the wavelength bandwidth of the AO coupling and the channel and/or band spacing. VOA assembly 150 provides broadband operation, spectral attenuation and broadband tilt adjustment. VOA assembly 150 can provide approximate flat spectral attenuation or it can provide a tilt adjustment by moving the match to one side or the other. This can require network feedback from a spectral monitor. Further, two VOA assemblies 150 can be in series, with one providing tile and the other overall attenuation.

Referring now to Figure 29, a channel equalizer 159 is illustrated. When used for a single wavelength channel, VOA 152 is likely to be positioned in an optical node incorporating a demultiplexer 160, such as an arrayed wave-guide grating (AWG) router. For example, VOA 152 can be used to equalize the powers of multiple channels and/or bands including, in particular, added channels and bands. In this case, the RF power and frequency for each VOA

152 is set differently according to the attenuation desired for each channel and/or band VOA 152 is to deal with. Polarization dependence of each VOA 152 is largely tolerated due to the feedback operation as long as the feedback speed is faster than the polarization fluctuations. For example, the characteristic time of SOP fluctuation in a real communication system can be on the order of a millisecond.

Demultiplexer 160 is configured to receive a plurality of different WDM channels and separate the different signals (channels) into different fibers, one fiber for each wavelength channel and/or bands. Each separate channel or band is individually attenuated with a VOA 152. This provides individual control for each channel or band. Some of the channels or bands can be dropped and not passed to VOA's 152. New channels or bands can be added after demultiplexer 160. VOA's 152 provide gain flattening and also permit adding and dropping of channels and/or bands. VOA's 152 provide spectral flattening and adjust the powers so the recombined signals all have a predetermined power.

In the Figure 29 embodiment, a first series of VOA's 152 is positioned between the drop and add and a second series of VOA's 152 positioned after the add. A multiplexer 162 is positioned downstream from the second series of VOA's 152. A monitor 164 is coupled to the output. Monitor 164 can provide a feedback signal that is used to adjust VOA's 152. The embodiment of Figure 29 provides broadband operation, variable spectral attenuation, channel/band by channel/band spectral attenuation and broadband tilt adjustment.

Referring now to Figure 30, one embodiment of an optical cross-connect apparatus 166 is provided. Optical cross-connect apparatus 166 provides channel routing, switching and leveling between two inputs with multiple channels or bands and two outputs of multiple channels or bands. Optical cross-connect apparatus 166 includes demultiplexer 160, multiplexer 162, a demultiplexer 168 and a multiplexer 170 and coupled to optical cross connect 172 which includes any number of devices to redirect channels or bands, including but not limited to mirrors and the like. Optical cross connect 172 can be made using MEMS mirrors, bubble switch technology, liquid crystals and the like. A plurality of VOA's 152 are each coupled to an optical fiber and

positioned between optical cross connect 172 and multiplexers 162 and 170. VOA's 152 are included to individually adjust the power of individual channels or bands and achieve leveling and/or spectral grooming.

Optionally included is a monitor 174 which can be a spectral monitor and the like that monitors the spectral output. A system command device 176 is coupled to a feedback control to receive network commands for a feedback loop. These network commands can, (i) come from the end of the link after electrical detection and bit error rate measurements, (ii) come from spectral monitors located throughout the network and (iii) can be IP signals or proprietary signals to the local control electronics/processor. A second monitor 178 is provided at the second output. The embodiment illustrated in Figure 30 also provides broadband operation, spectral attenuation and channel by channel broadband spectral adjustment.

Referring now to Figure 31, another embodiment of an optical cross-connect apparatus 180 includes two or more optical cross connects 172 and 182. At least two demultiplexers 160 and 184 are provided at the input carrying WDM signals. At least two multiplexers 162 and 184 are at the output. Each group goes to a cross connect. As illustrated in Figure 31, there are two groups and each goes to optical cross connect 172 and 182. The channels or bands are split into two or more groups. Each group goes to a different cross connect.

There can be any number of different groups. Each channel or band can be its own group. In one embodiment, the number of channels or bands can equal the number of cross connects. For example all the $\lambda 1$ go to one cross connect, $\lambda 2$ to a second, .$\lambda 3$ to a third and the like. This prevents two channels or bands from being on top of each other in one fiber. All of the even channels or bands can be in one group and the odd channels or bands in the other group.

In the Figure 31 embodiment, one group of channels or bands is directed to optical cross connect 172 and the other group is directed to optical cross connect 182. Thereafter, multiplexers 162 and 184 combine the different channels or bands which are directed to the different output fibers. A plurality of VOA's 152 are coupled to optical cross connects 172 and 182. Spectral monitors 174 couple the output fibers with VOA's 152. Amplifiers 186 can be

coupled to the optical fibers carrying the WDM signals. It will be appreciated that the embodiment of Figure 31 can be extended to any desired number of optical cross connects, demultiplexers and multiplexers.

For a wavelength channel or band it only one VOA is needed to be included between the demultiplexer and the multiplexer. Only one degree of freedom is required for each channel or band. All the VOA's are preferably at either the input or at the output of the cross connect. Alternatively, VOA's can be positioned at both the input and the output. Spectral monitors are preferably at the output fibers. The spectral monitors send information to the feedback loop coupled to the VOA's. Network commands can go to the feedback control. This provides the target spectrum. Feedback control goes from a tap in the fiber, to the spectral monitor and then to the feedback control and then to the VOA. The feedback control has an input from the spectral monitor and another from the network commands which provides the target spectrum.

The foregoing description of a preferred embodiment of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise forms disclosed. Obviously, many modifications and variations will be apparent to practitioners skilled in this art. It is intended that the scope of the invention be defined by the following claims and their equivalents.

What is claimed is:

CLAIMS:

1. An optical communication assembly, comprising:

an optical cross connect coupled to a first, a second, a third and a fourth set of optical fibers;

a first demultiplexer coupled to a first input fiber and the first set of optical fibers;

a second demultiplexer coupled to a second input fiber and the second set of optical fibers;

a first multiplexer coupled to a first output fiber and the third set of optical fibers;

a second multiplexer coupled to a second output fiber and the fourth set of optical fibers; and

a first set of attenuators coupled to the third set of optical fibers and a second set of attenuators coupled to the fourth set of optical fibers.

2. The assembly of claim 1, wherein the optical cross connect provides channel or band routing between the first and second input fibers to the first and second output fibers.

3. The assembly of claim 1, wherein the optical cross connect provides channel or band routing and switching between the first and second input fibers to the first and second output fibers.

4. The assembly of claim 1, wherein the optical cross connect provides channel or band routing, switching and leveling between the first and second input fibers to the first and second output fibers.

5. The assembly of claim 1, further comprising:

a first spectral monitor coupled to the first output fiber and at least a portion of the first set of attenuators.

6. The assembly of claim 5, further comprising:

a first network command device coupled to the first spectral monitor and the at least a portion of the first set of attenuators, the first spectral monitor and the first network command device forming a first closed feedback loop.

7. The assembly of claim 6, further comprising:

a second spectral monitor coupled to the second output fiber and at least a portion of the second set of attenuators.

8. The assembly of claim 7, further comprising:

a second network command device coupled to the second spectral monitor and the at least a portion of the second set of attenuators, the second spectral monitor and the second network command device forming a second closed feedback loop.

9. The assembly of claim 1, wherein the first and second demultiplexers are each an arrayed wave-guide grating.

10. The assembly of claim 1, wherein each of the first and second demultiplexers is configured to receive a plurality of different WDM channels or bands and direct the different channels or bands into the first and second sets of optical fibers.

11. The assembly of claim 1, wherein each optical fiber of the first and second sets of optical fibers receives a different channel or band from the first and second demultiplexers.

12. The assembly of claim 1, wherein each attenuator of the first and second sets of attenuators is a variable optical attenuator.

13. The assembly of claim 1, wherein each attenuator is coupled to a single channel or band.

14. The assembly of claim 1, wherein the power of each channel or band passed by the first multiplexer and the first output fiber, and the second multiplexer and the second output fiber is individually controllable.

15. The assembly of claim 1, wherein each of an attenuator includes an acoustic wave generator that produces multiple acoustic signals with individual controllable strengths, and frequencies and each of the acoustic signals provides a coupling between a core mode and a different spatial mode.

16. The assembly of claim 15, wherein each acoustic wave generator generates a transverse wave.

17. The assembly of claim 15, wherein each acoustic wave generator generates a longitudinal wave.

18. The assembly of claim 15, wherein each acoustic wave generator generates a torsional wave.

19. The assembly of claim 1, wherein an optical fiber coupled to an attenuator has a single core mode guided along a core.

20. The assembly of claim 1, wherein an optical fiber coupled to an attenuator has a multiple modes guided along a core.

21. The assembly of claim 1, wherein an optical fiber coupled to an attenuator provides fundamental and cladding mode propagation.

22. The assembly of claim 1, wherein an optical fiber coupled to an attenuator sufficiently tensioned to reduce losses in the acoustic wave.

23. The assembly of claim 1, further comprising:
a spectral monitor positioned at an output of the multiplexer.

24. The assembly of claim 1, further comprising:
a plurality of detectors coupled to the plurality of attenuators.

25. The assembly of claim 1, further comprising:
an acoustic damper coupled to each attenuator optical fiber.

26. An optical communication assembly, comprising:
an optical cross connect coupled to a first, a second, a third and a fourth set of optical fibers;
a first demultiplexer coupled to a first input fiber and the first set of optical fibers;
a second demultiplexer coupled to a second input fiber and the second set of optical fibers;

a first multiplexer coupled to a first output fiber and the third set of optical fibers;

a second multiplexer coupled to a second output fiber and the fourth set of optical fibers; and

a first set of attenuators coupled to the first set of optical fibers and a second set of attenuators coupled to the second set of optical fibers.

27. The assembly of claim 26, wherein the optical cross connect provides channel or band routing between the first and second input fibers to the first and second output fibers.

28. The assembly of claim 26, wherein the optical cross connect provides channel or band routing and switching between the first and second input fibers to the first and second output fibers.

29. The assembly of claim 26, wherein the optical cross connect provides channel or band routing, switching and leveling between the first and second input fibers to the first and second output fibers.

30. The assembly of claim 26, further comprising:

a first spectral monitor coupled to the first output fiber and at least a portion of the first set of attenuators.

31. The assembly of claim 30, further comprising:

a first network command device coupled to the first spectral monitor and the at least a portion of the first set of attenuators, the first spectral monitor and the first network command device forming a first closed feedback loop.

32. The assembly of claim 31, further comprising:

a second spectral monitor coupled to the second output fiber and at least a portion of the second set of attenuators.

33. The assembly of claim 32, further comprising:

a second network command device coupled to the second spectral monitor and the at least a portion of the second set of attenuators, the second

spectral monitor and the second network command device forming a second closed feedback loop.

34. The assembly of claim 26, wherein the first and second demultiplexers are each an arrayed wave-guide grating.

35. The assembly of claim 26, wherein each of the first and second demultiplexers is configured to receive a plurality of different WDM channels or bands and direct the different channels or bands into the first and second sets of optical fibers.

36. The assembly of claim 26, wherein each optical fiber of the first and second sets of optical fibers receives a different channel or band from the first and second demultiplexers.

37. The assembly of claim 26, wherein each attenuator of the first and second sets of attenuators is a variable optical attenuator.

38. The assembly of claim 26, wherein each attenuator is coupled to a single channel or band.

39. The assembly of claim 26, wherein a power of each channel or band passed by the first multiplexer and the first output fiber, and the second multiplexer and the second output fiber is individually controllable.

40. The assembly of claim 26, wherein attenuator includes an acoustic wave generator that produces multiple acoustic signals with individual controllable strengths and frequencies, and each of the acoustic signals provides a coupling between the core mode and a different spatial mode.

41. The assembly of claim 40, wherein each acoustic wave generator generates a transverse wave.

42. The assembly of claim 40, wherein each acoustic wave generator generates a longitudinal wave.

43. The assembly of claim 40, wherein each acoustic wave generator generates a torsional wave.

44. The assembly of claim 26, wherein an optical fiber coupled to an attenuator has a single core mode guided along the core.

45. The assembly of claim 26, wherein an optical fiber coupled to an attenuator has multiple modes guided along the core.

46. The assembly of claim 26, wherein an optical fiber coupled to an attenuator provides fundamental and cladding mode propagation.

47. The assembly of claim 26, wherein an optical fiber coupled to an attenuator is sufficiently tensioned to reduce losses in the acoustic wave.

48. The assembly of claim 26, further comprising:
a spectral monitor positioned at an output of the multiplexer.

49. The assembly of claim 26, further comprising:
a plurality of detectors coupled to the plurality of attenuators.

50. The assembly of claim 26, further comprising:
an acoustic damper coupled to each attenuator optical fiber.

51. An optical communication assembly, comprising:
a demultiplexer coupled to an input fiber;
a multiplexer coupled to an output fiber;
a plurality of optical fibers, each of an optical fiber being coupled to one or both of the demultiplexer and multiplexer; and
a plurality of attenuators each coupled to an optical fiber of the plurality of optical fibers, each attenuator including,
an attenuator optical fiber with a longitudinal axis, a core and a cladding in a surrounding relationship to the core, the attenuator optical fiber having a plurality of guided core modes,
an acoustic wave propagation member with a proximal end and a distal end, the distal end being coupled to the attenuator optical fiber, the

acoustic wave propagation member propagating an acoustic wave from the proximal to the distal end and launch an acoustic wave in the attenuator optical fiber,

at least one acoustic wave generator coupled to the proximal end of the acoustic wave propagation member.

52. The assembly of claim 51, wherein the demultiplexer is an arrayed wave-guide grating.

53. The assembly of claim 51, wherein the demultiplexer is configured to receive a plurality of different WDM channels or bands and direct the different channels or bands into optical fibers of the plurality of optical fibers.

54. The assembly of claim 53, wherein each optical fiber receives a different channel or band from the demultiplexer.

55. The assembly of claim 51, wherein each attenuator is a variable optical attenuator.

56. The assembly of claim 51, wherein the optical communication assembly is a channel equalizer.

57. The assembly of claim 51, wherein at least a portion of the channels or bands passed by the multiplexer and the output fiber are individually attenuated by one of the attenuators in the plurality of attenuators.

58. The assembly of claim 51, wherein at least a portion of the channels or bands passed by the multiplexer and the output fiber are individually controllable.

59. The assembly of claim 51, wherein at least one optical fiber of the plurality of optical fibers is not coupled to the demultiplexer and adds at least one channel or band.

60. The assembly of claim 51, wherein at least one optical fiber of the plurality of optical fibers is not coupled to the multiplexer and drops at least one channel or band introduced to the demultiplexer by the input fiber.

61. The assembly of claim 51, wherein each acoustic wave generator produces multiple acoustic signals with individual controllable strengths and frequencies and each of the acoustic signals provides a coupling between the core mode and a different spatial mode.

62. The assembly of claim 51, wherein a length of the attenuator optical fiber is no greater than 1 meter.

63. The assembly of claim 51, wherein each acoustic wave generator generates a transverse wave.

64. The assembly of claim 51, wherein each acoustic wave generator generates a longitudinal wave.

65. The assembly of claim 51, wherein each acoustic wave generator generates a torsional wave.

66. The assembly of claim 51, wherein the attenuator optical fiber has a single core mode guided along the core.

67. The assembly of claim 51, wherein the attenuator optical fiber has multiple core modes guided along the core.

68. The assembly of claim 51, wherein the attenuator optical fiber provides fundamental and cladding mode propagation.

69. The assembly of claim 51, further comprising:
a spectral monitor positioned at an output of the multiplexer.

70. The assembly of claim 51, further comprising:
a plurality of detectors coupled to the plurality of attenuators.

71. The assembly of claim 51, further comprising:

an acoustic damper coupled to each attenuator optical fiber.

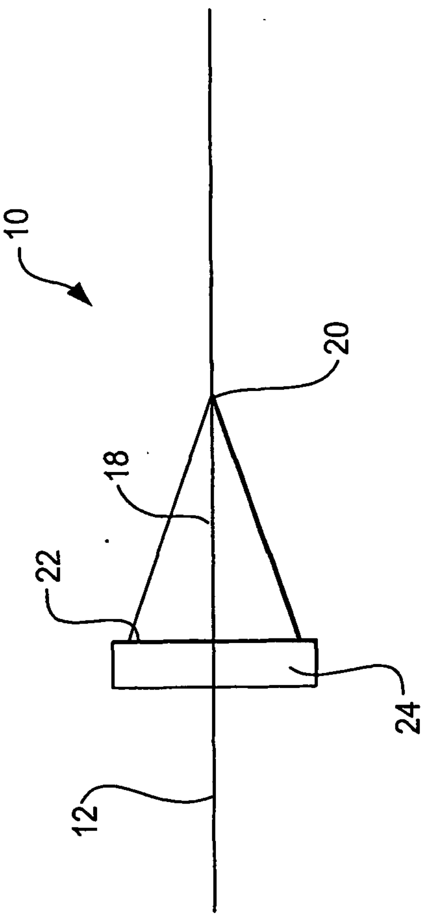

FIG. 1a

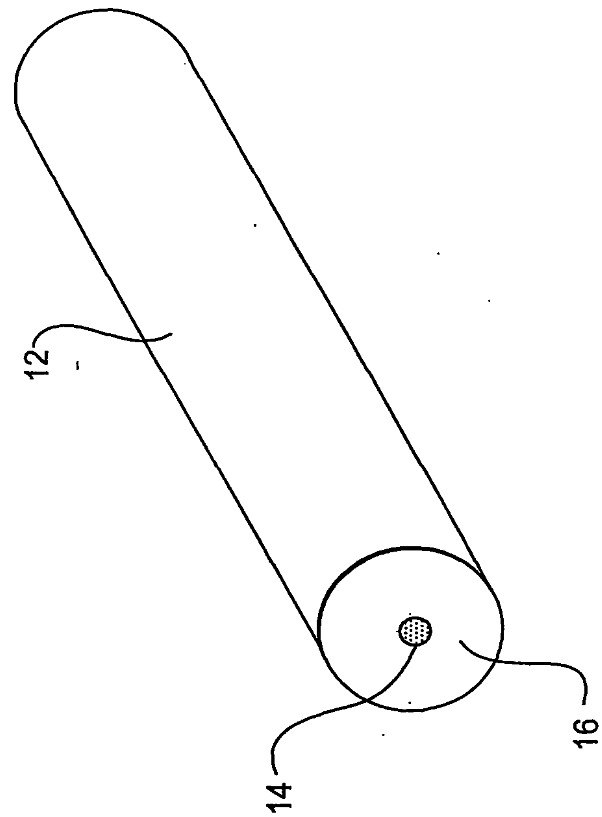

FIG. 1b

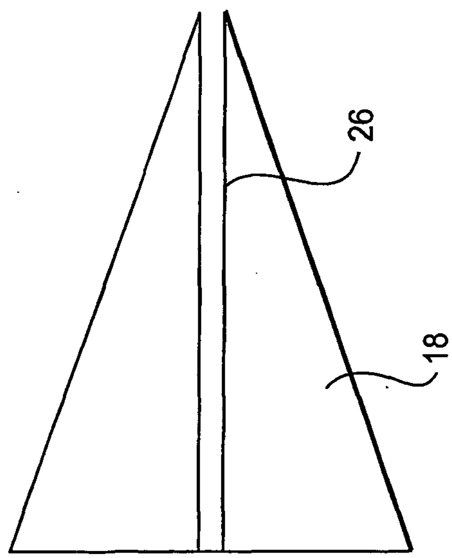

FIG. 2

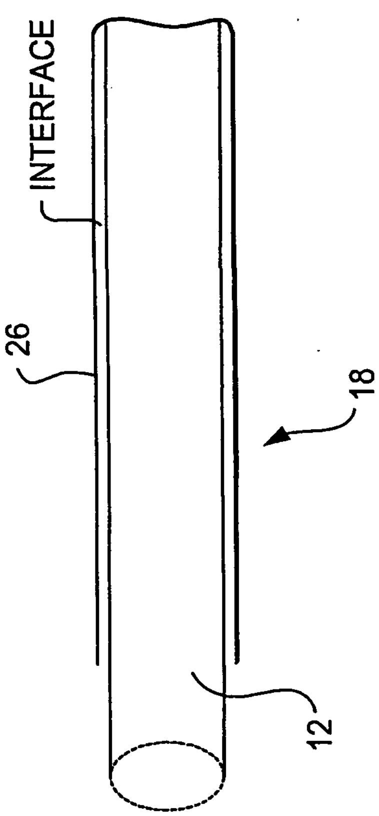

FIG. 3a

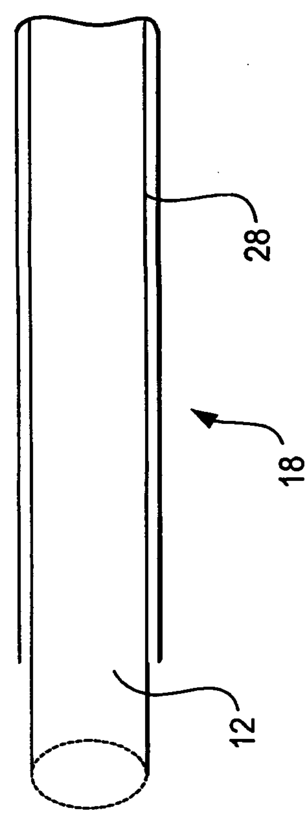

FIG. 3b

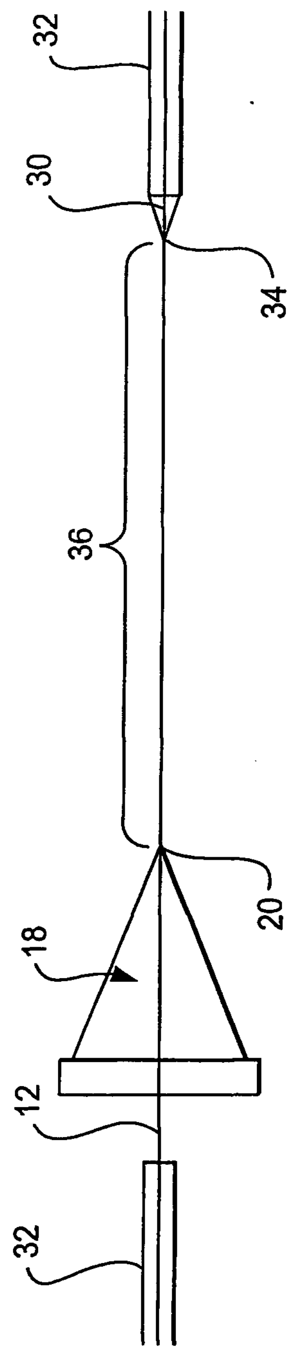

FIG. 4

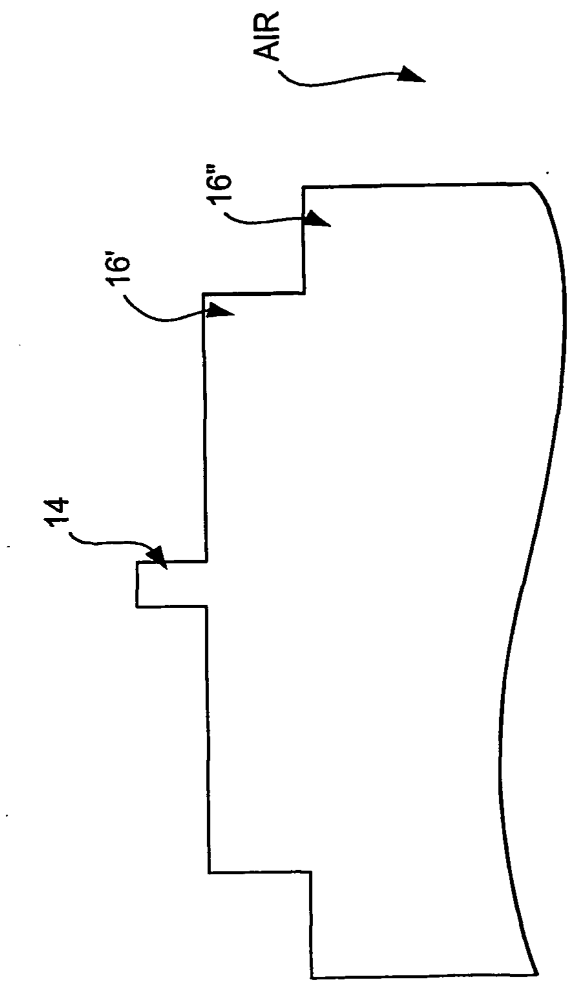

FIG. 5

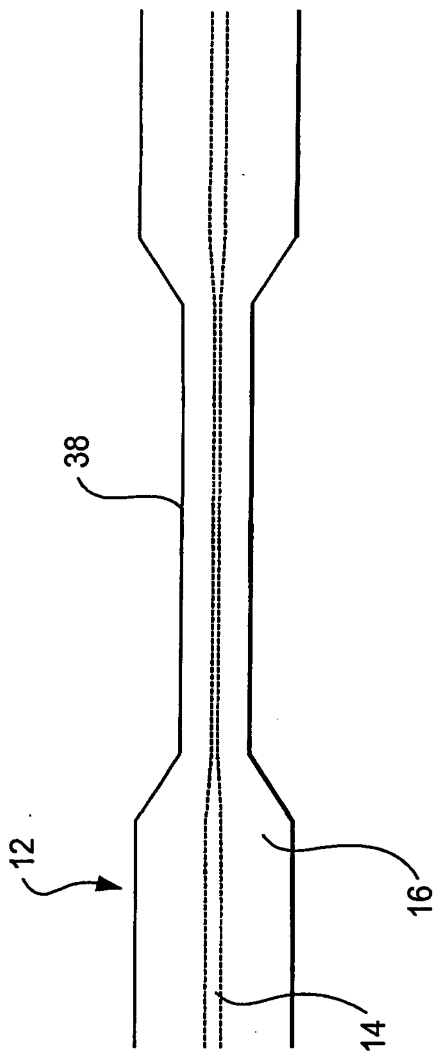

FIG. 6

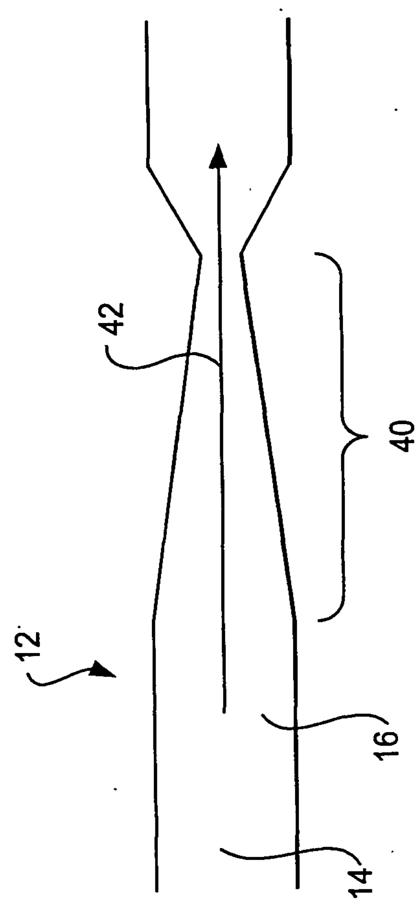

FIG. 7

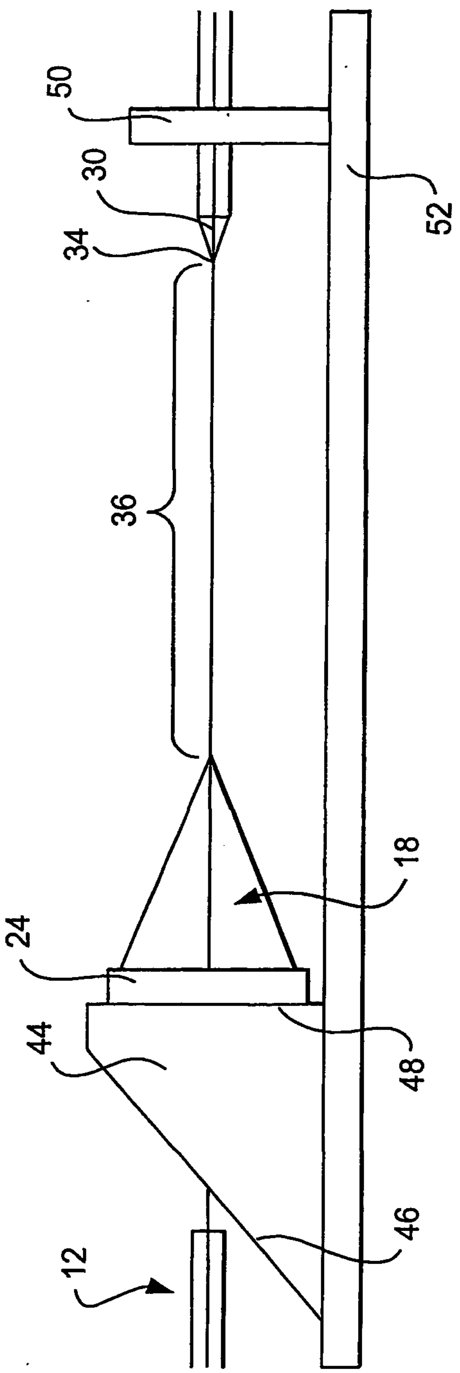

FIG. 8

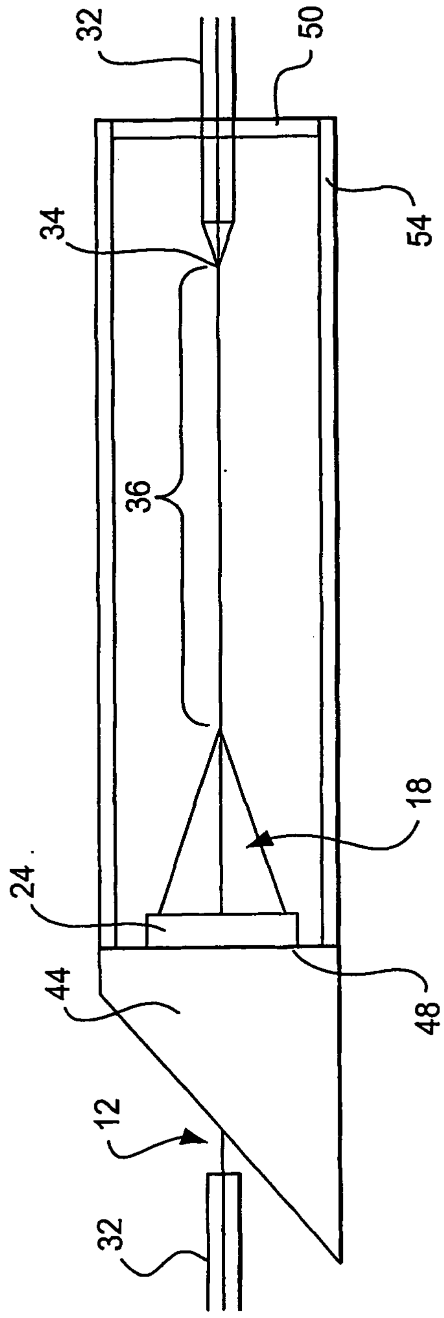

FIG. 9

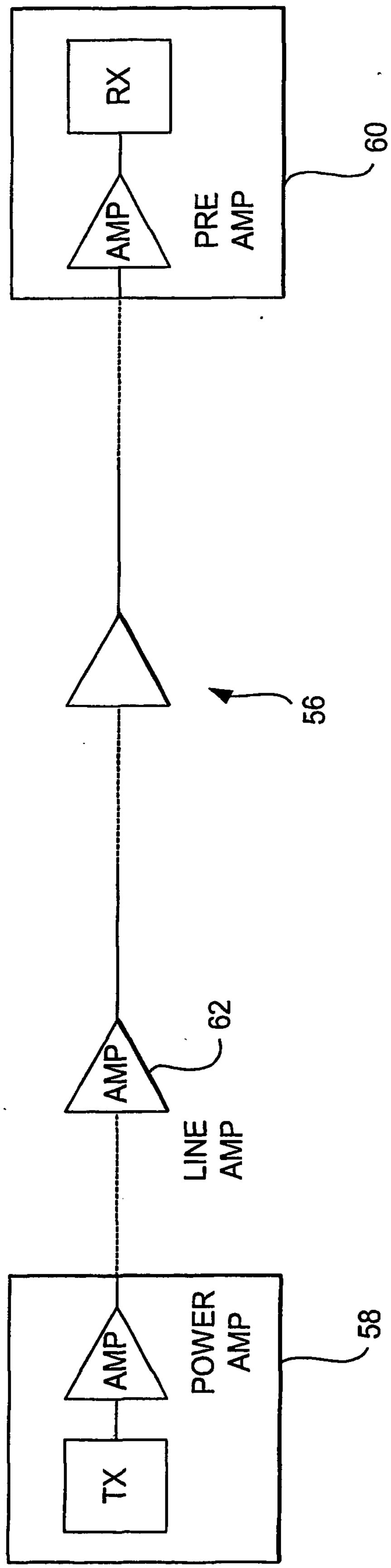

FIG. 10

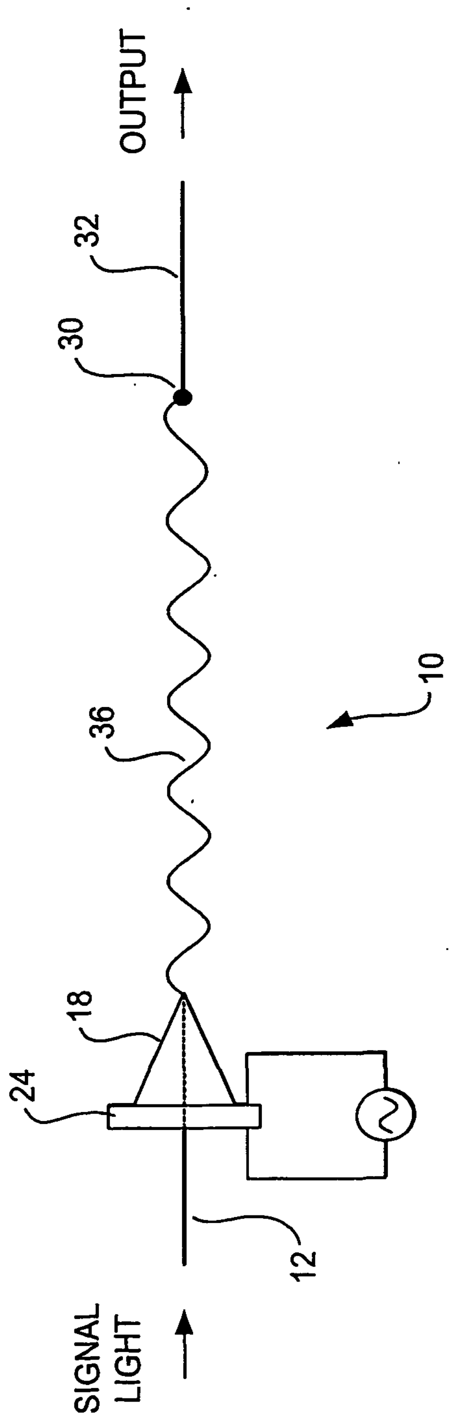

FIG. 11

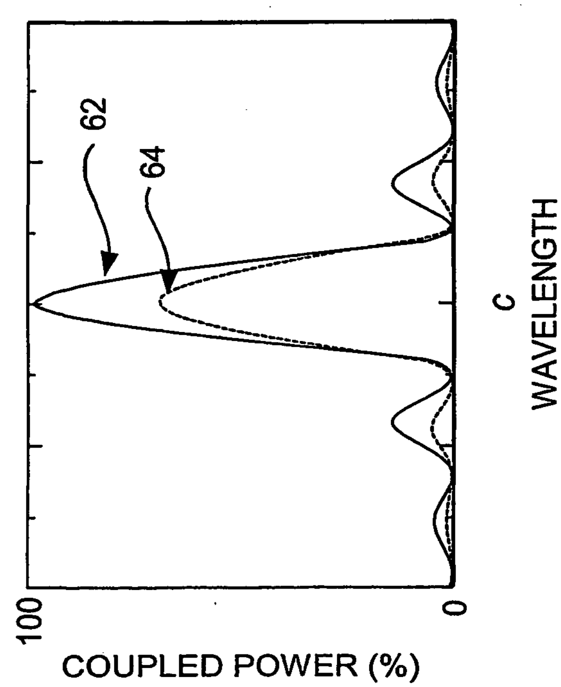

FIG. 12a

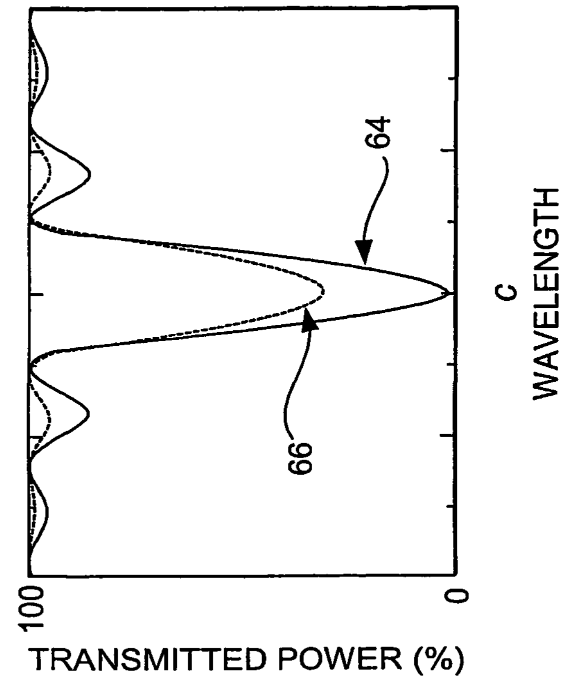

FIG. 12b

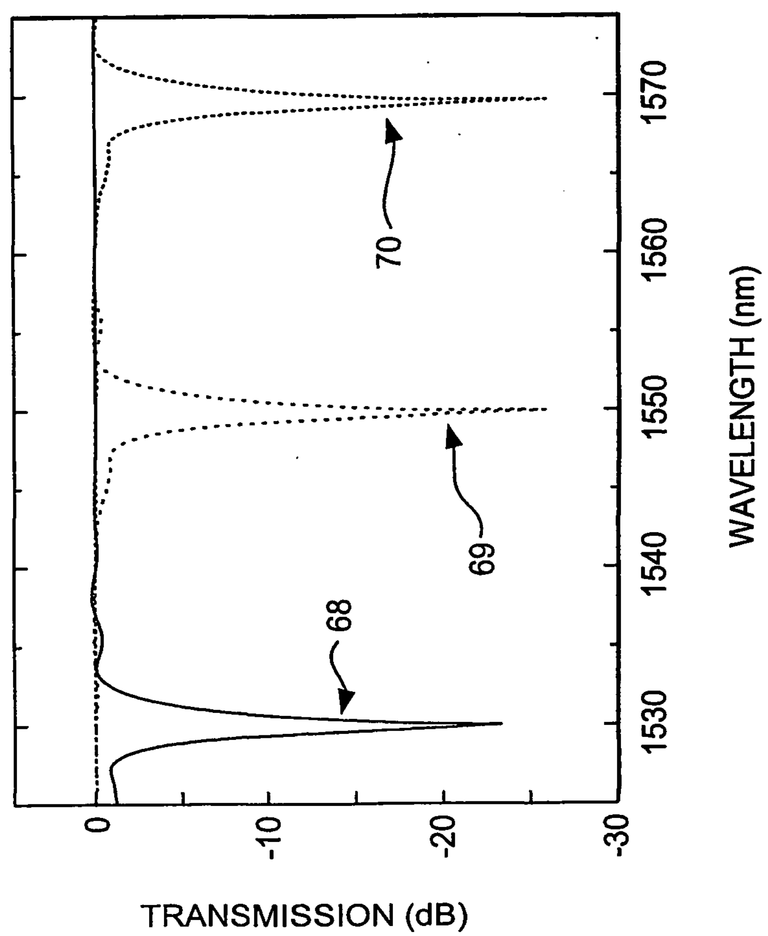
TRANSMISSION (dB)
0
-10
-20
-30
WAVELENGTH (nm)
1530
1540
1550
1560
1570
68
69
70

FIG. 13

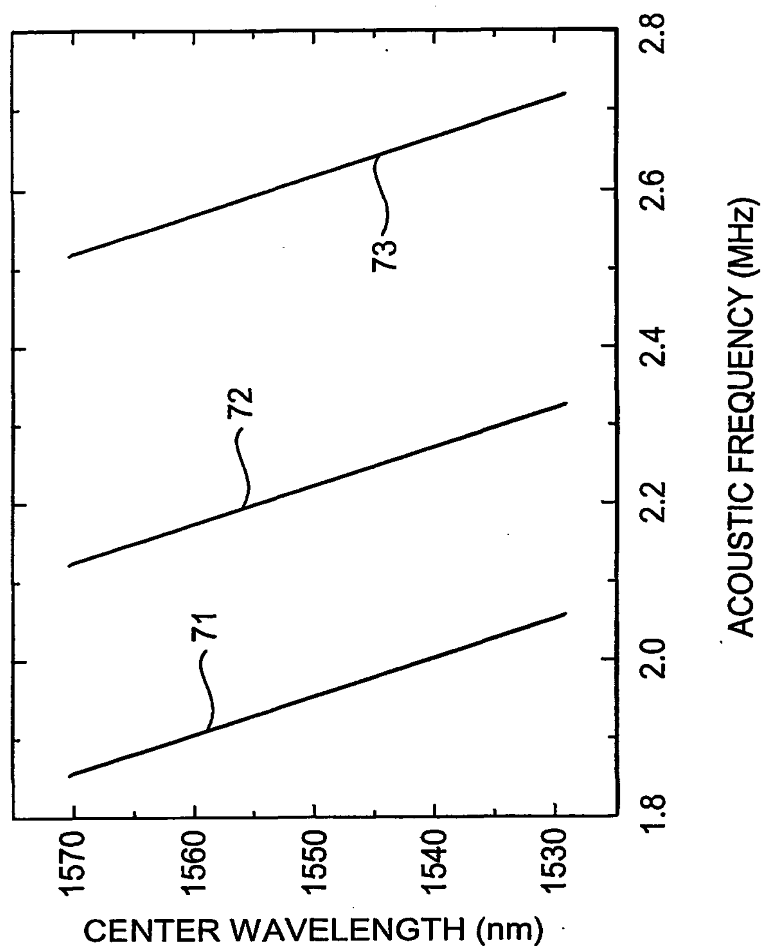
1570
1560
1550
1540
1530
CENTER WAVELENGTH (nm)
1.8
2.0
2.2
2.4
2.6
2.8
ACOUSTIC FREQUENCY (MHz)
71
72
73

FIG. 14

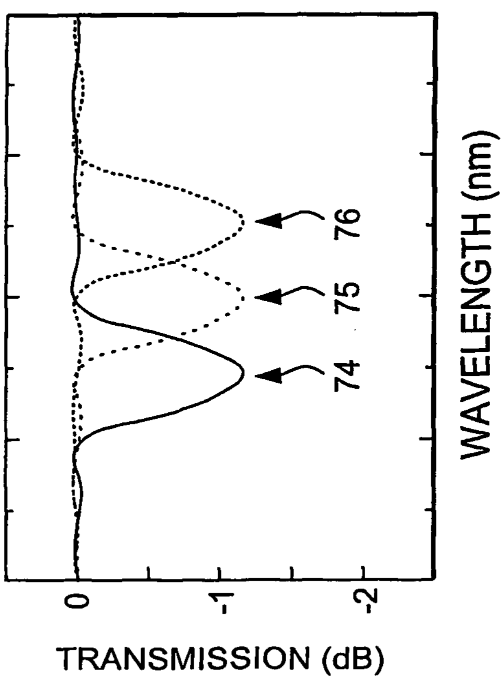

FIG. 15a

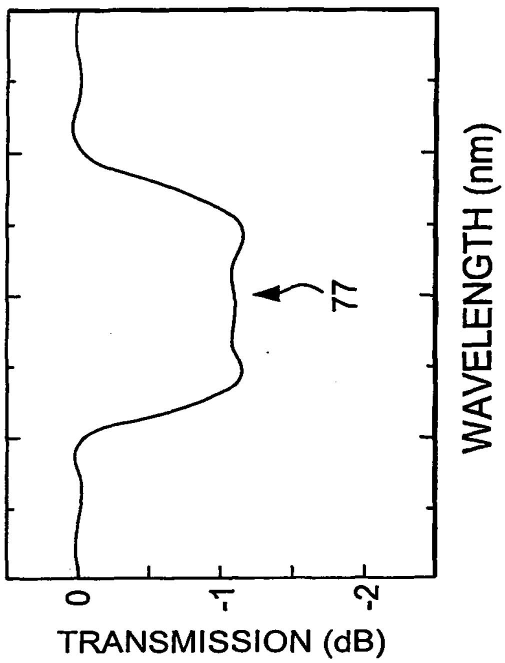

FIG. 15b

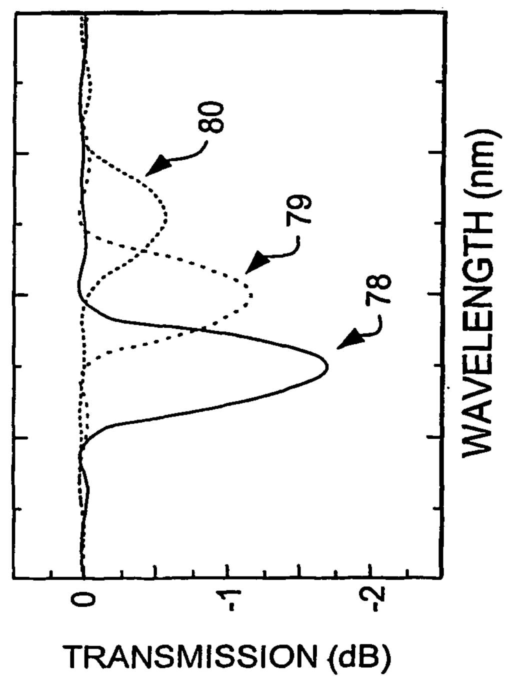

FIG. 15c

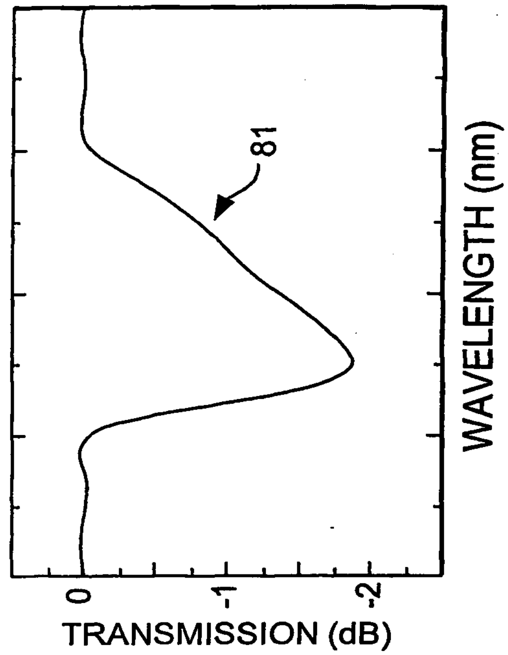

FIG. 15d

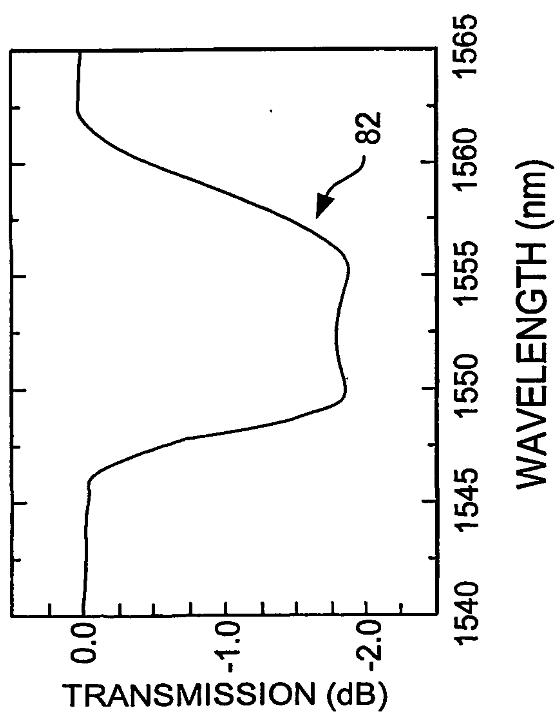

FIG. 16a

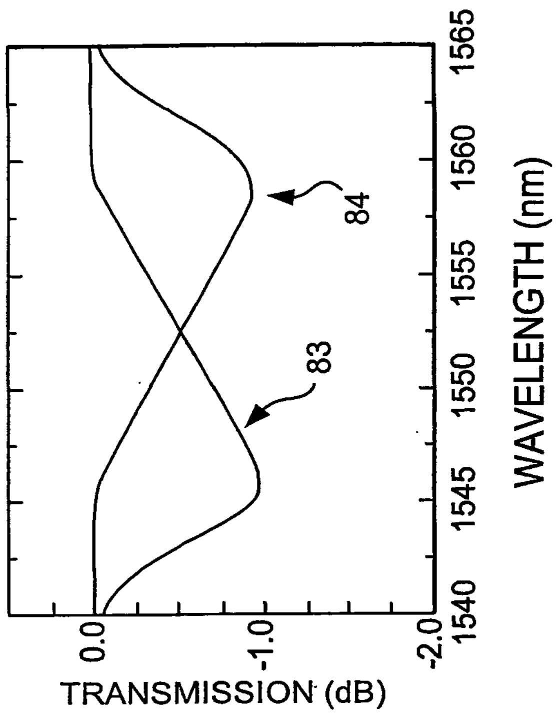

FIG. 16b

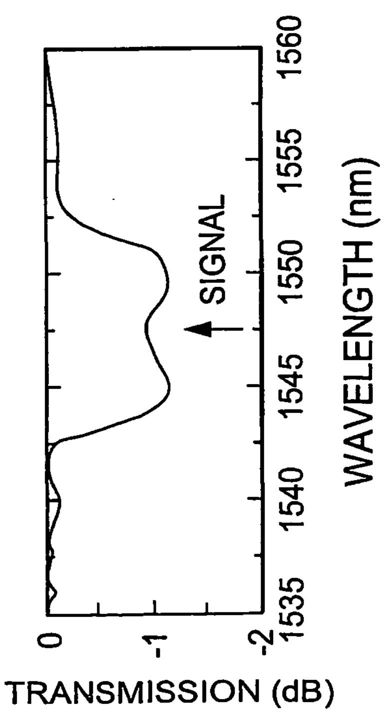

FIG. 17a

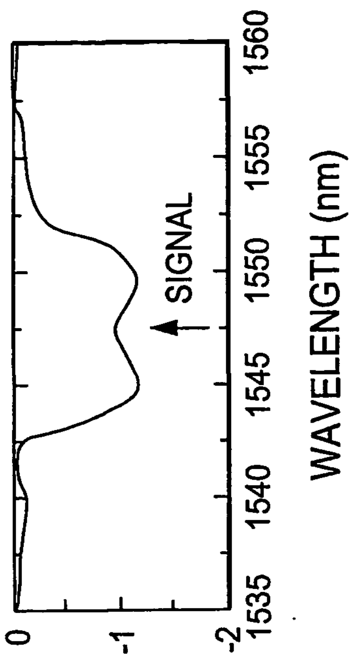

FIG. 17b

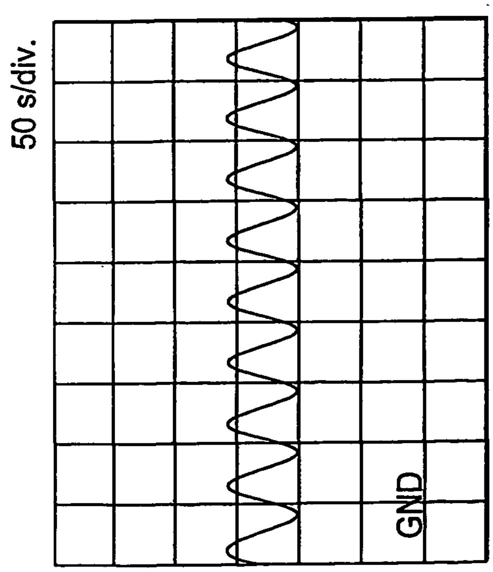

FIG. 17c

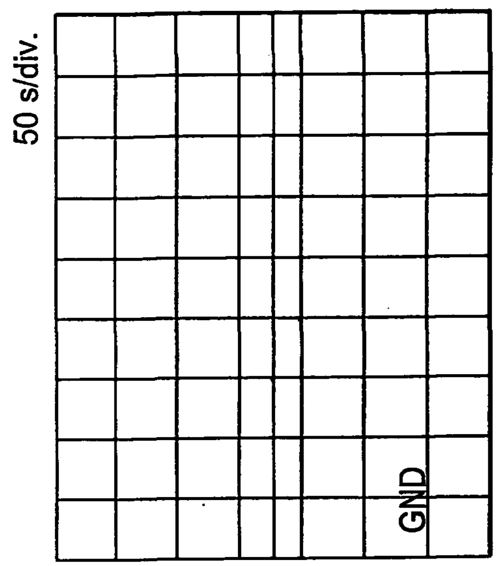

FIG. 17d

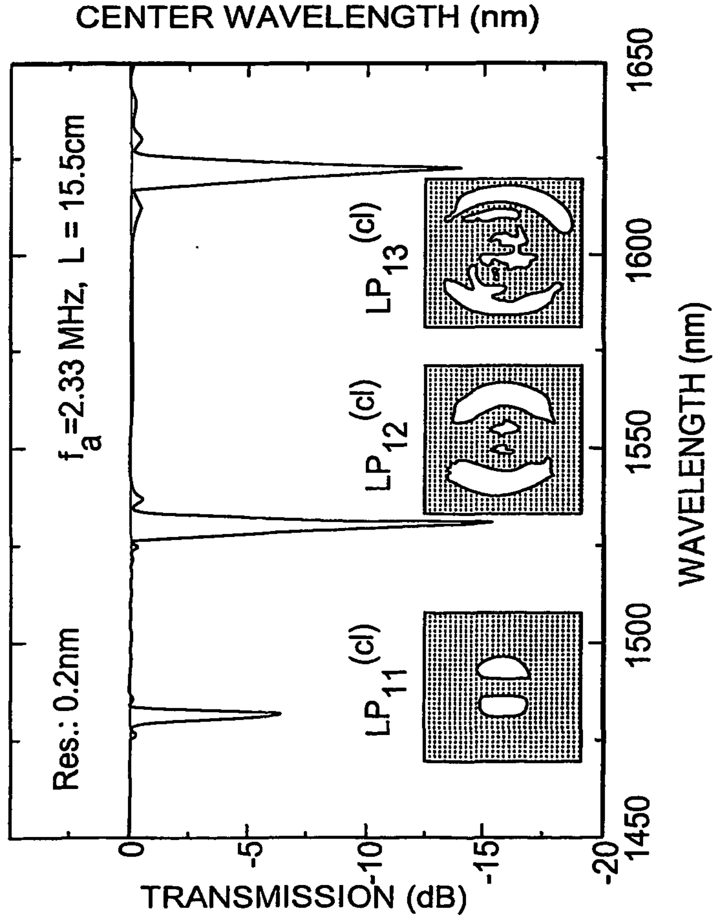

FIG. 18a

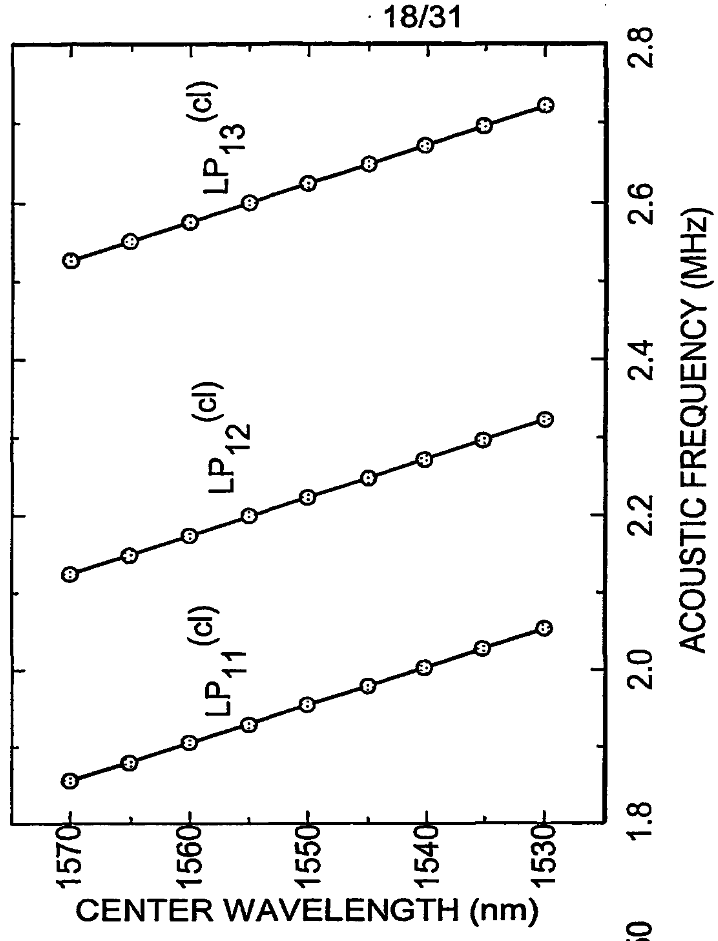

FIG. 18b

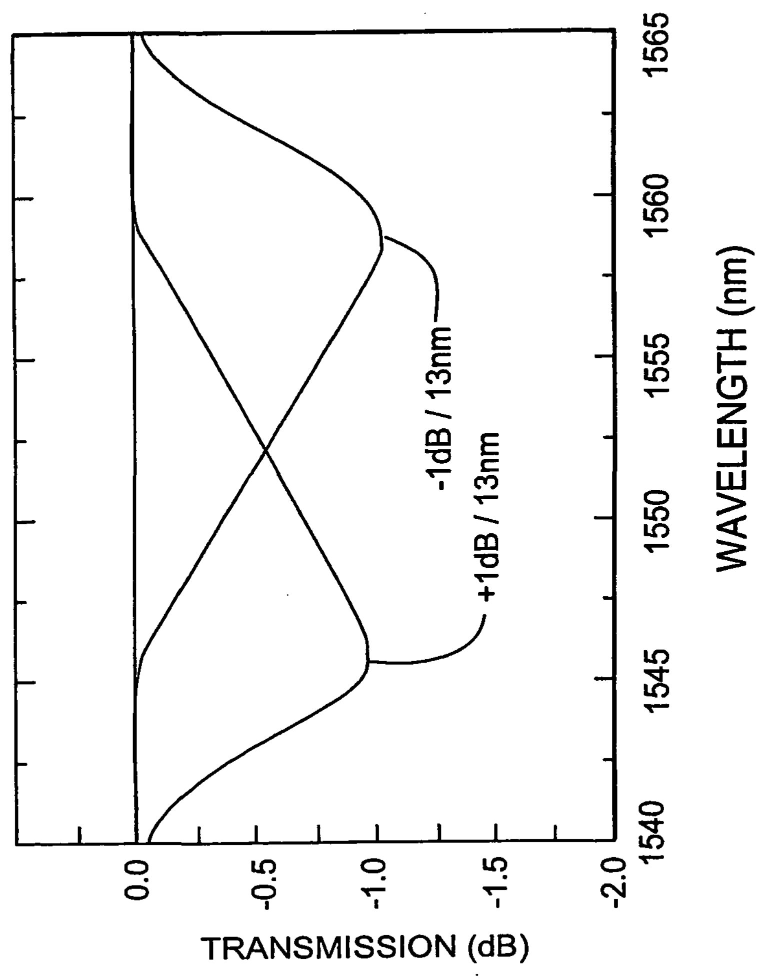
TRANSMISSION (dB)
0.0
-0.5
-1.0
-1.5
-2.0
1540
1545
1550
1555
1560
1565
WAVELENGTH (nm)
-1dB / 13nm
+1dB / 13nm

FIG. 19

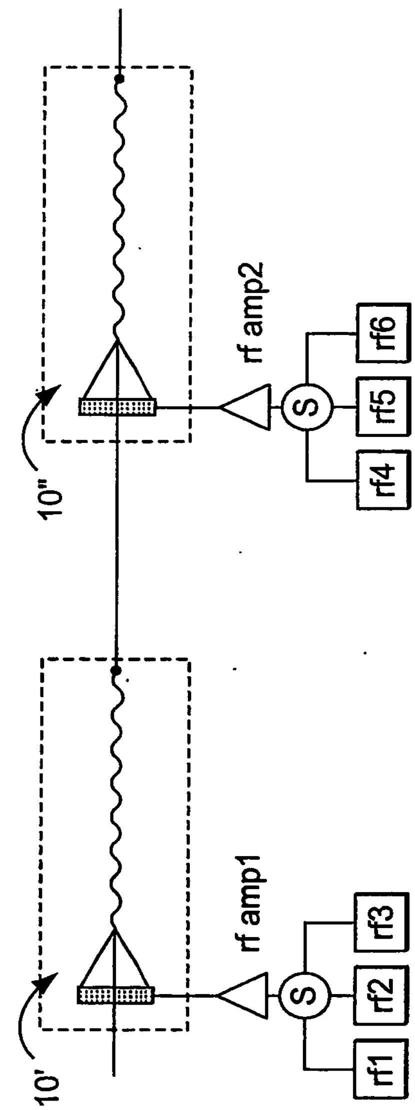

FIG. 20a

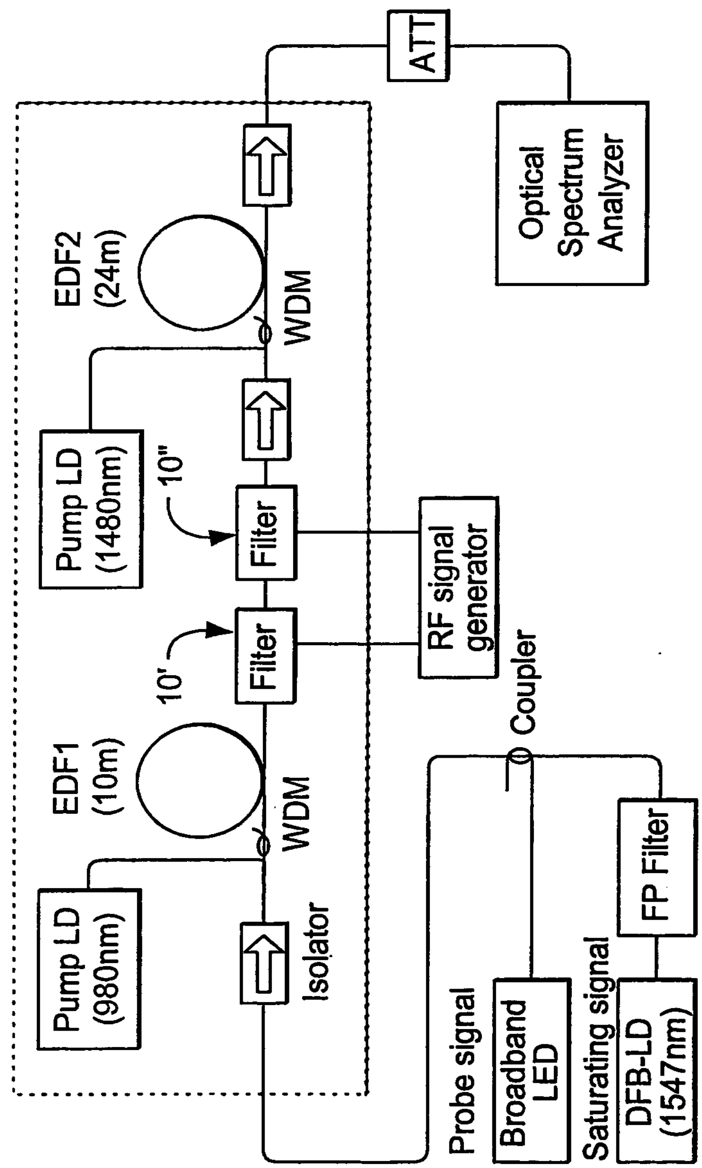

FIG. 20b

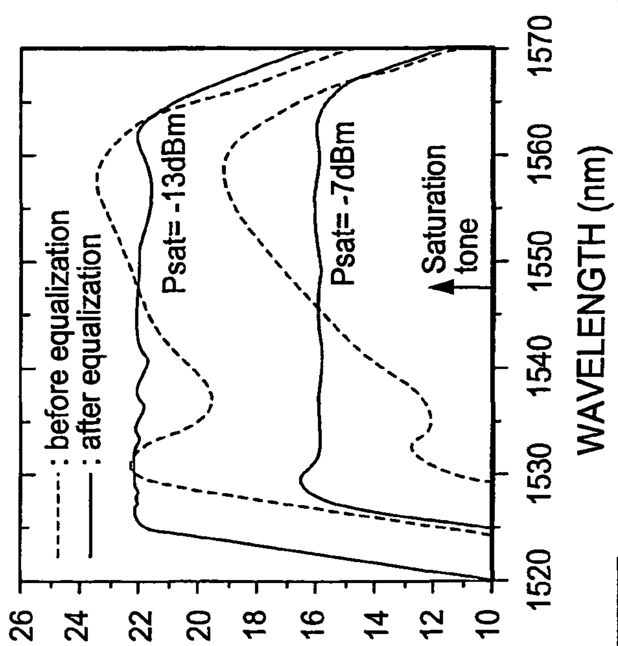

FIG. 21a

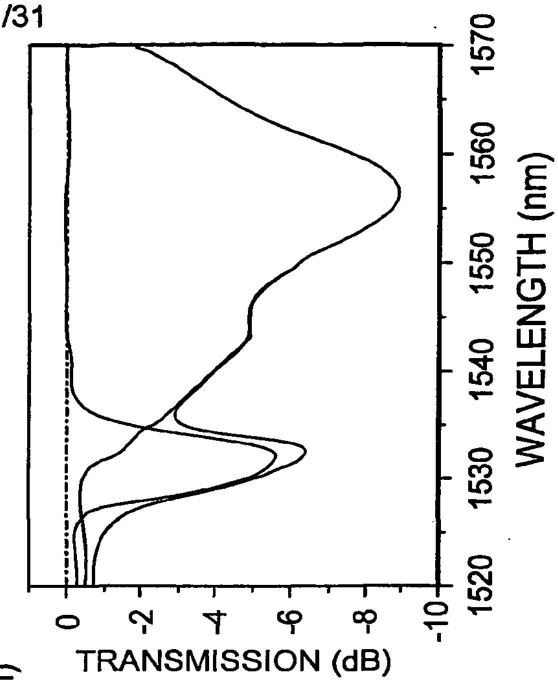

FIG. 21c

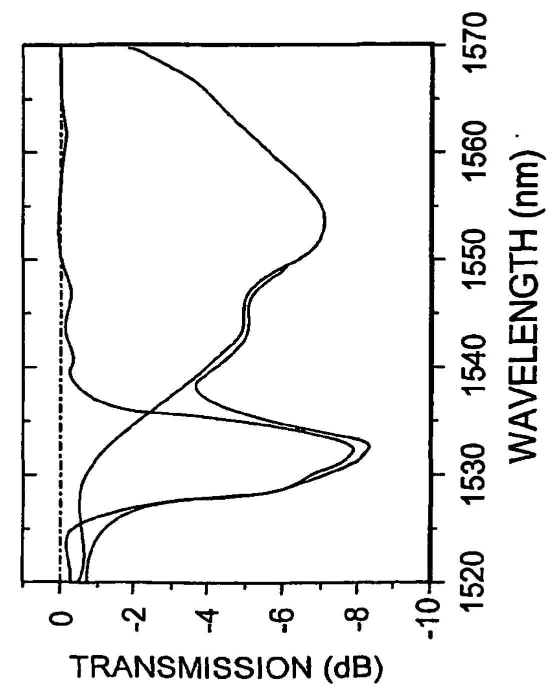

FIG. 21b

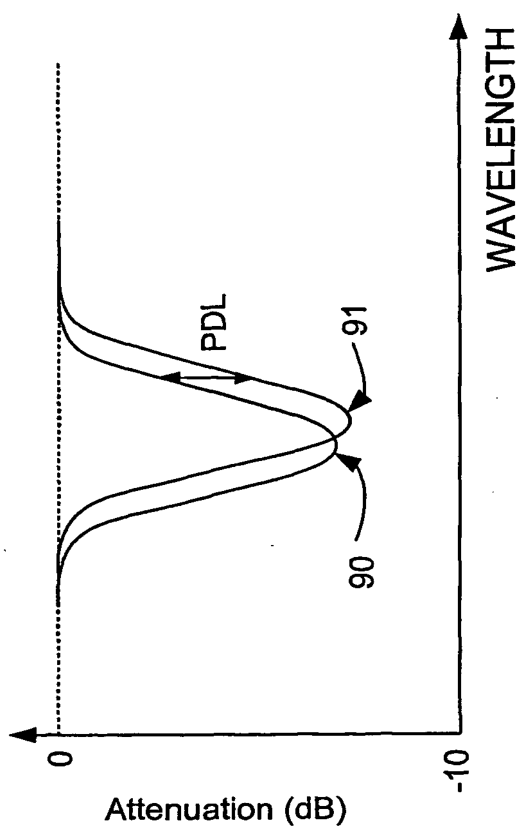

FIG. 22a

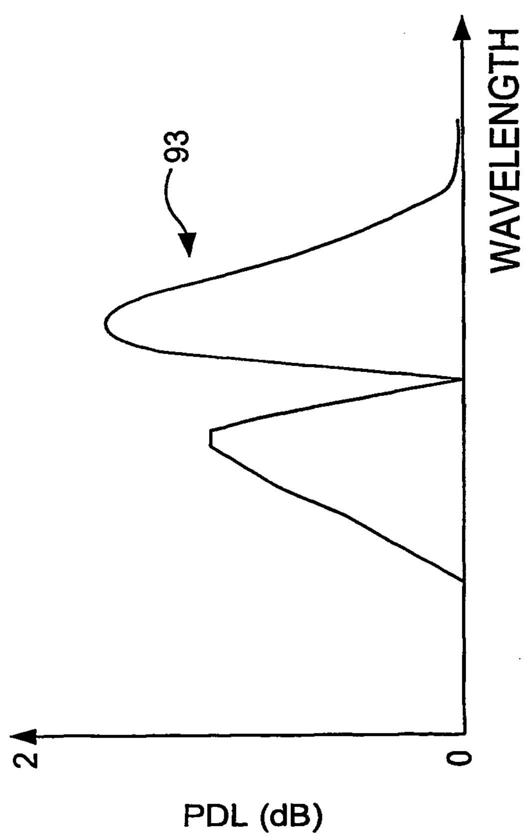

FIG. 22b

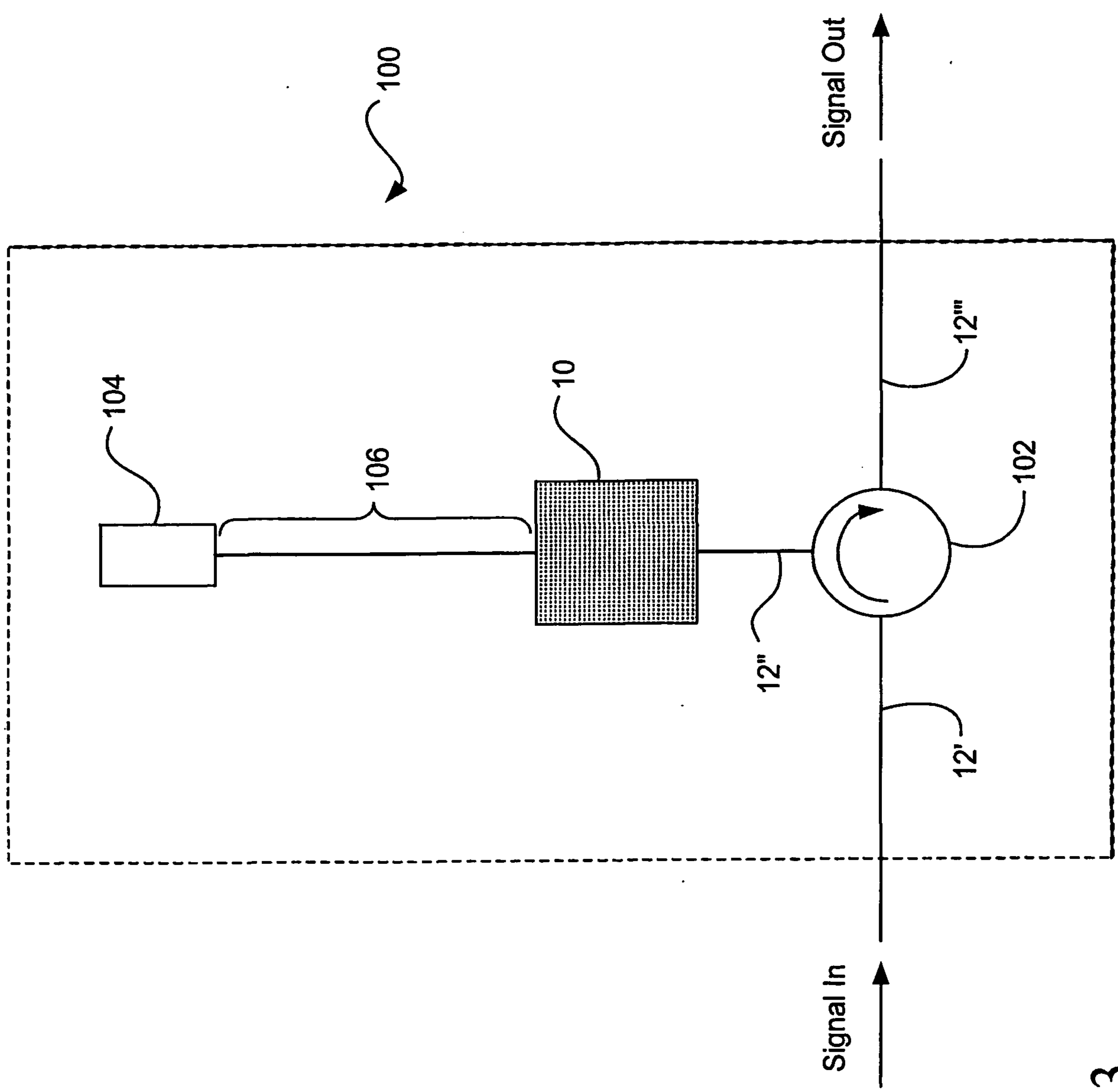

FIG. 23

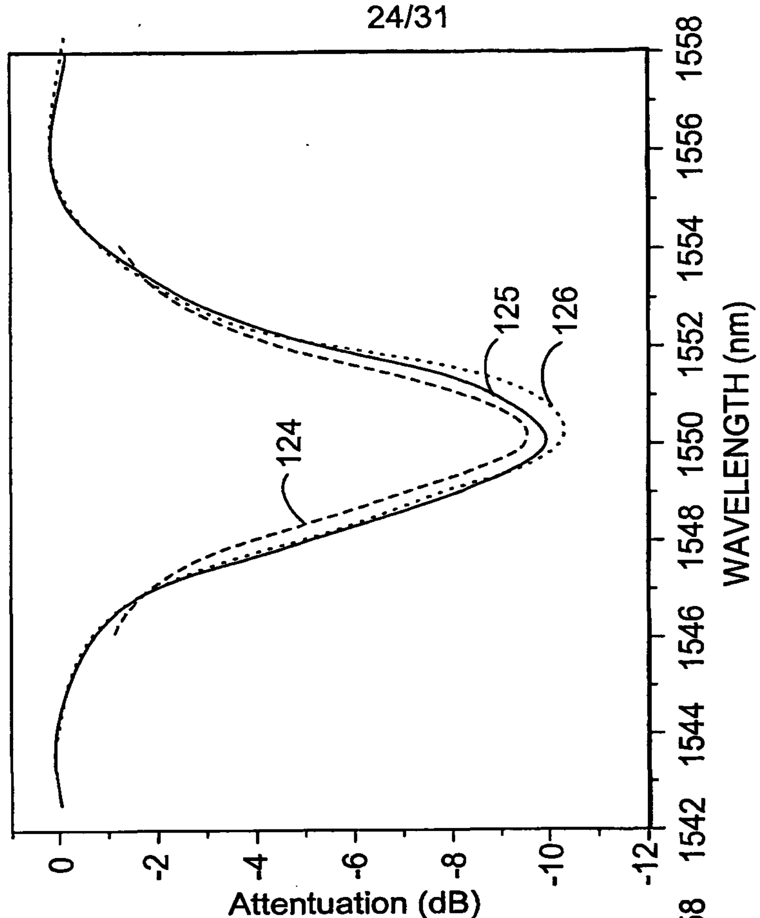

FIG. 24b

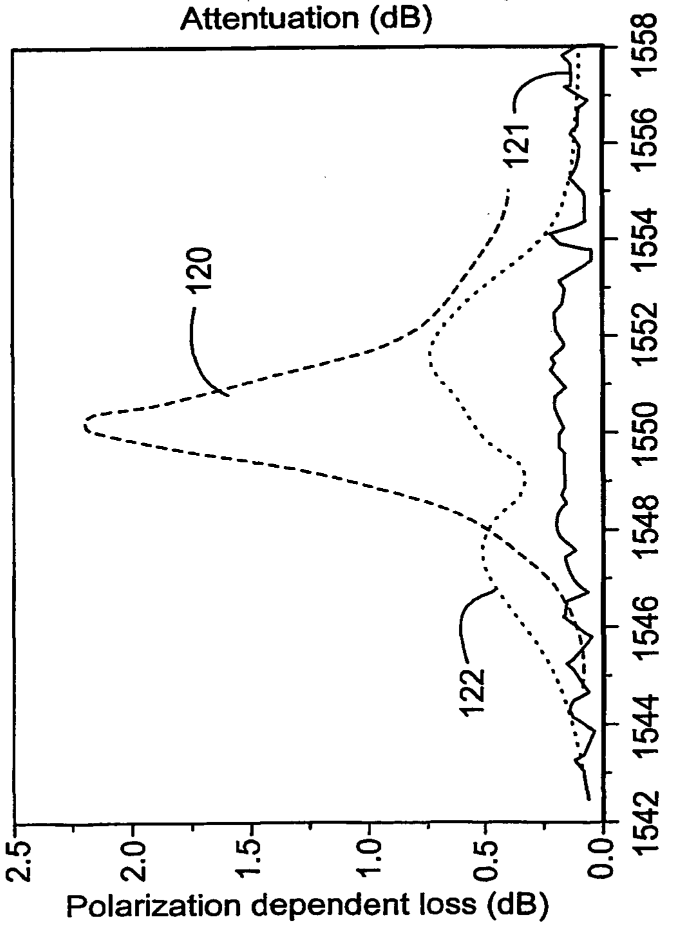

FIG. 24a

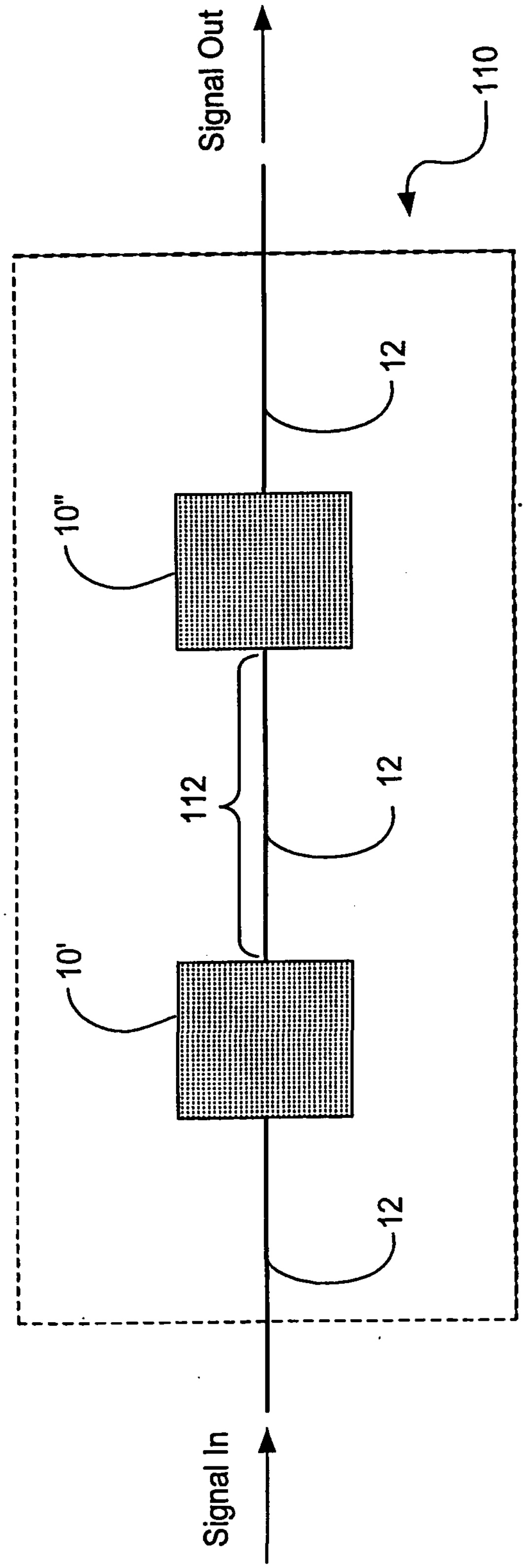

FIG. 25

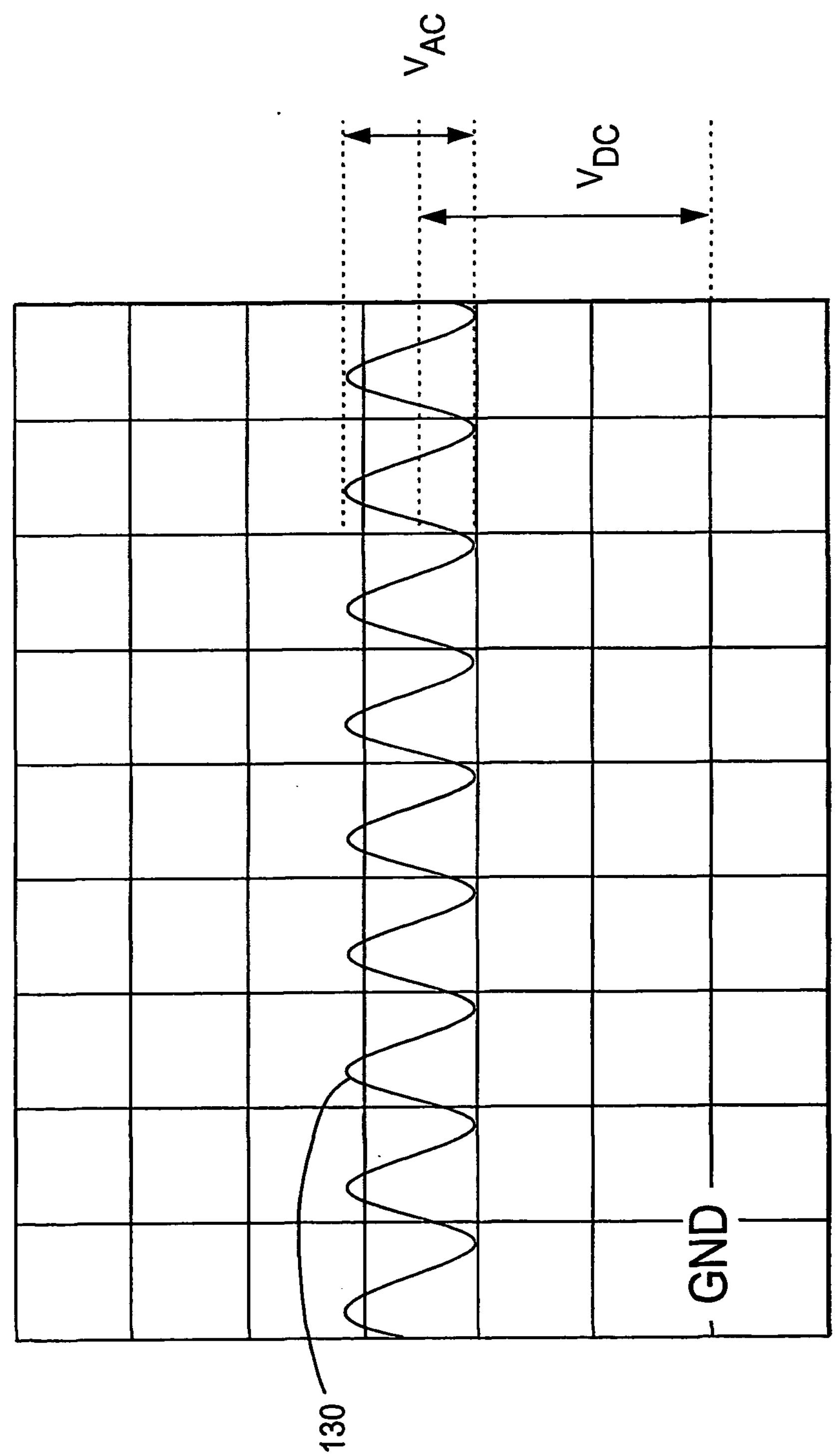

FIG. 26

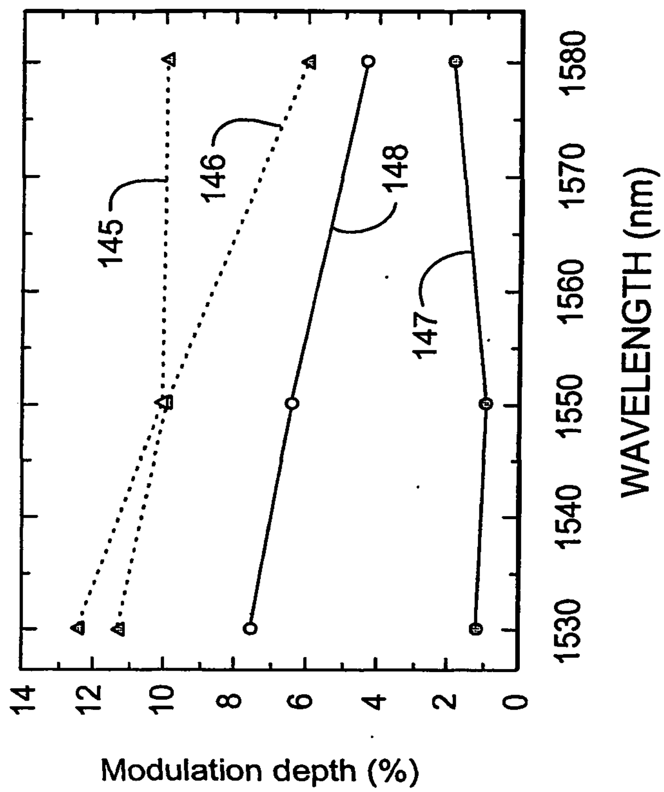

FIG. 27b

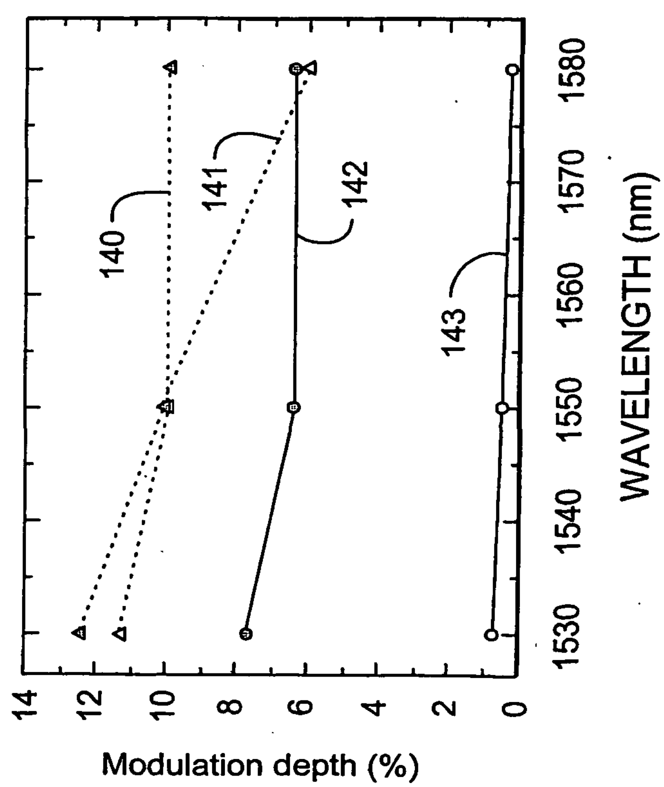

FIG. 27a

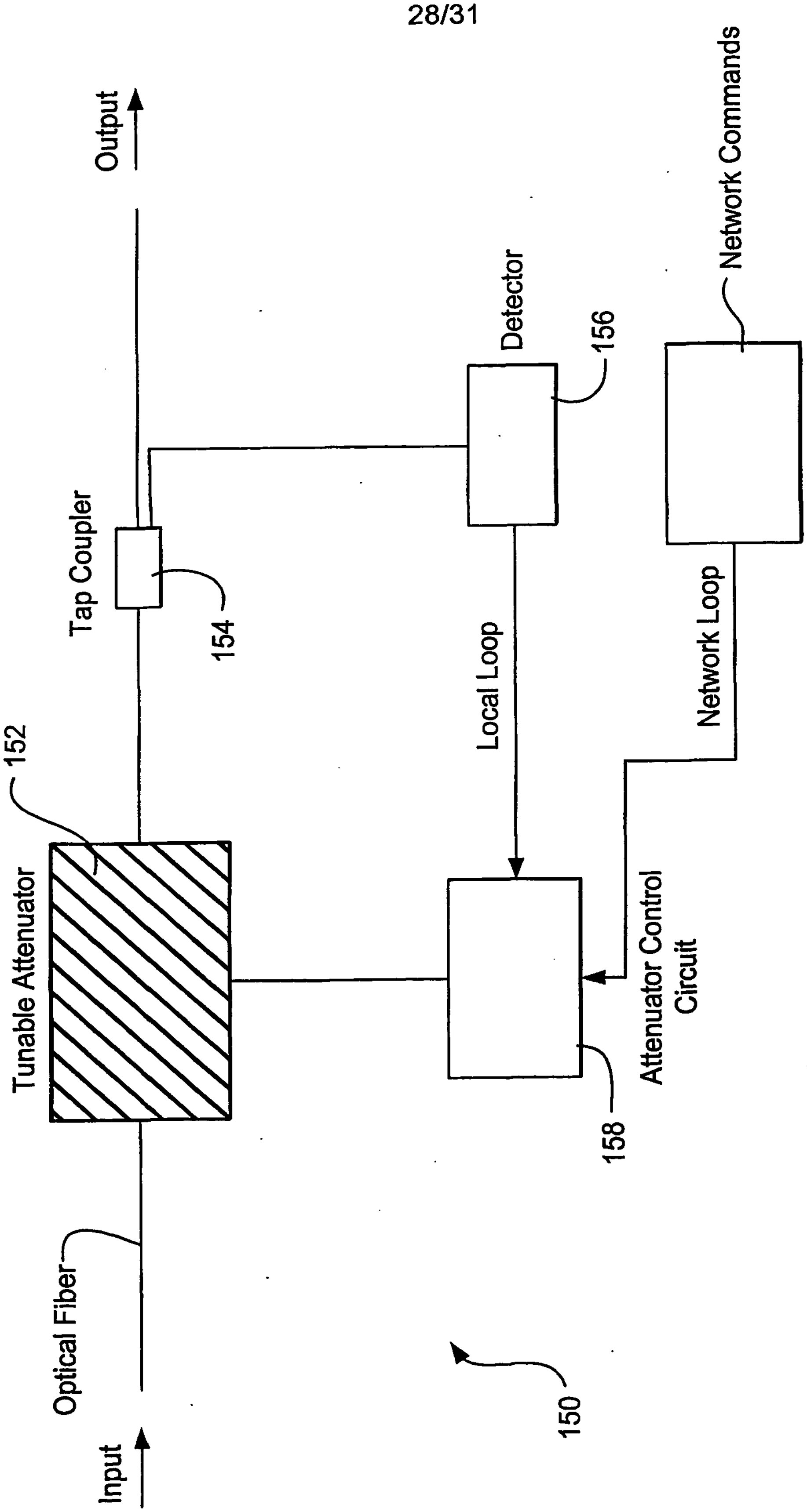
Output
Network Commands
Detector
156
Tap Coupler
154
Local Loop
Network Loop
152
Tunable Attenuator
Attenuator Control Circuit
158
Optical Fiber
150
Input

FIG. 28

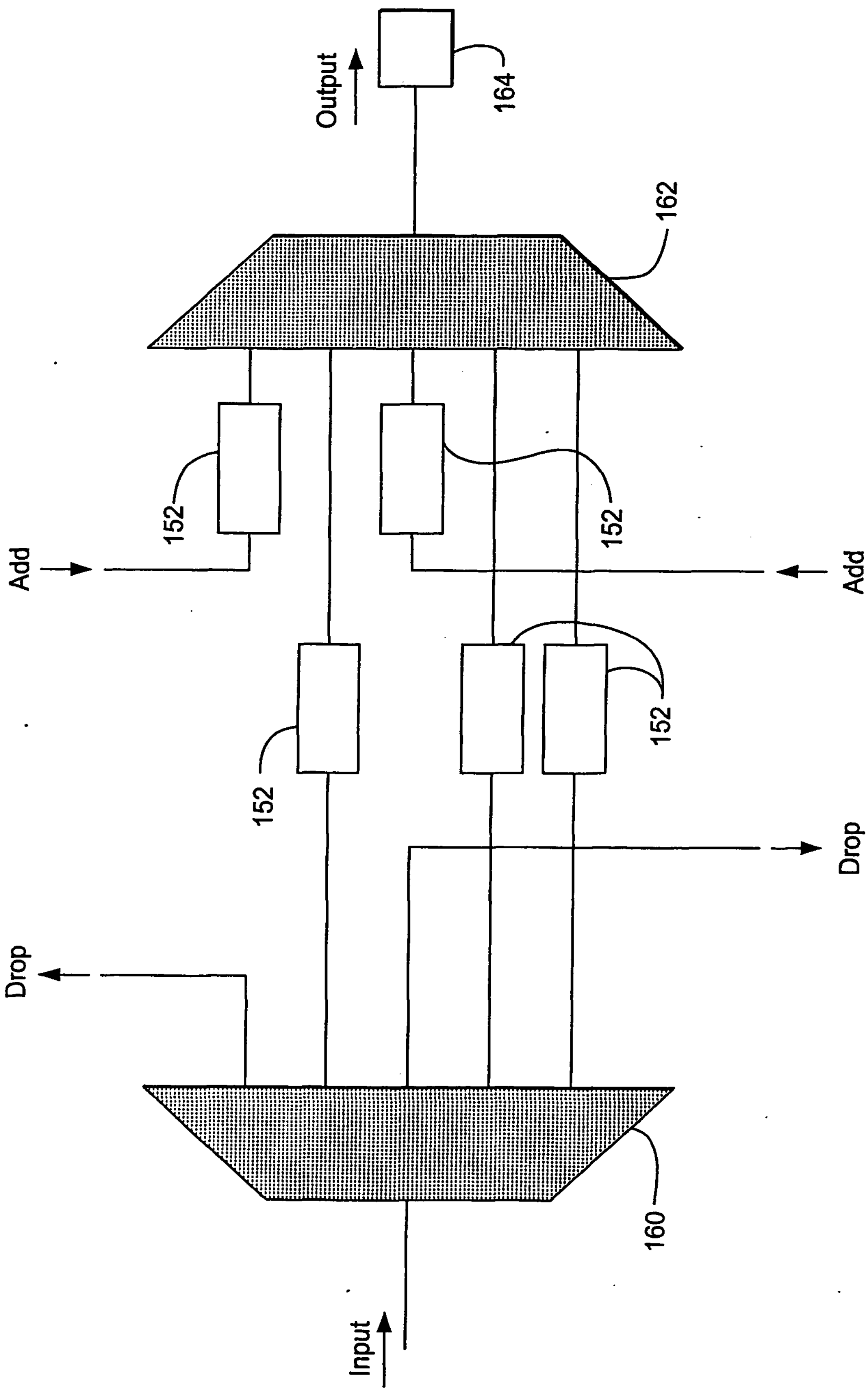

FIG. 29

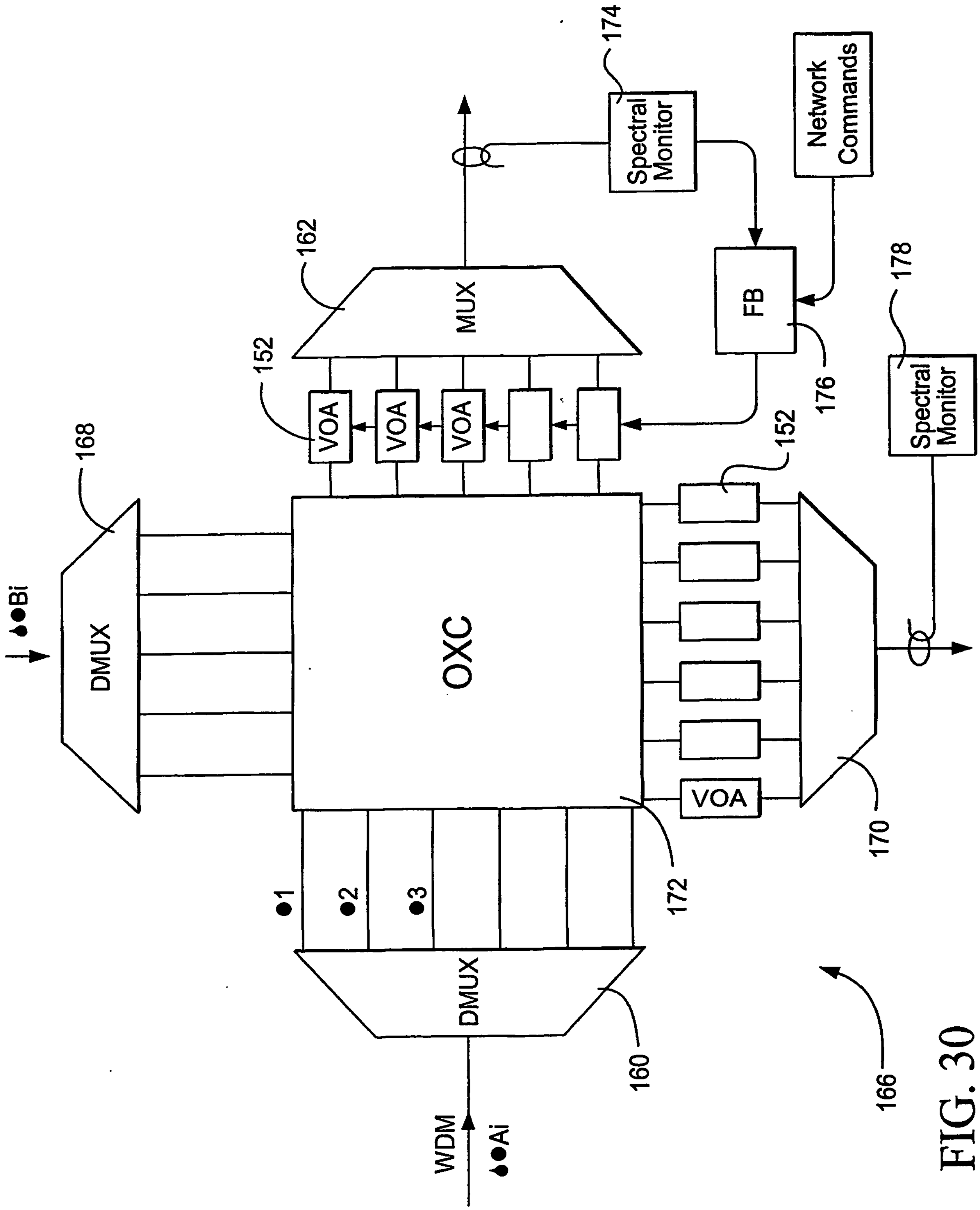
174
Spectral Monitor
Network Commands
162
MUX
FB
176
178
Spectral Monitor
152
VOA
VOA
VOA
168
152
DMUX
Bi
OXC
VOA
170
172
1
2
3
DMUX
160
WDM
Ai
166

FIG. 30

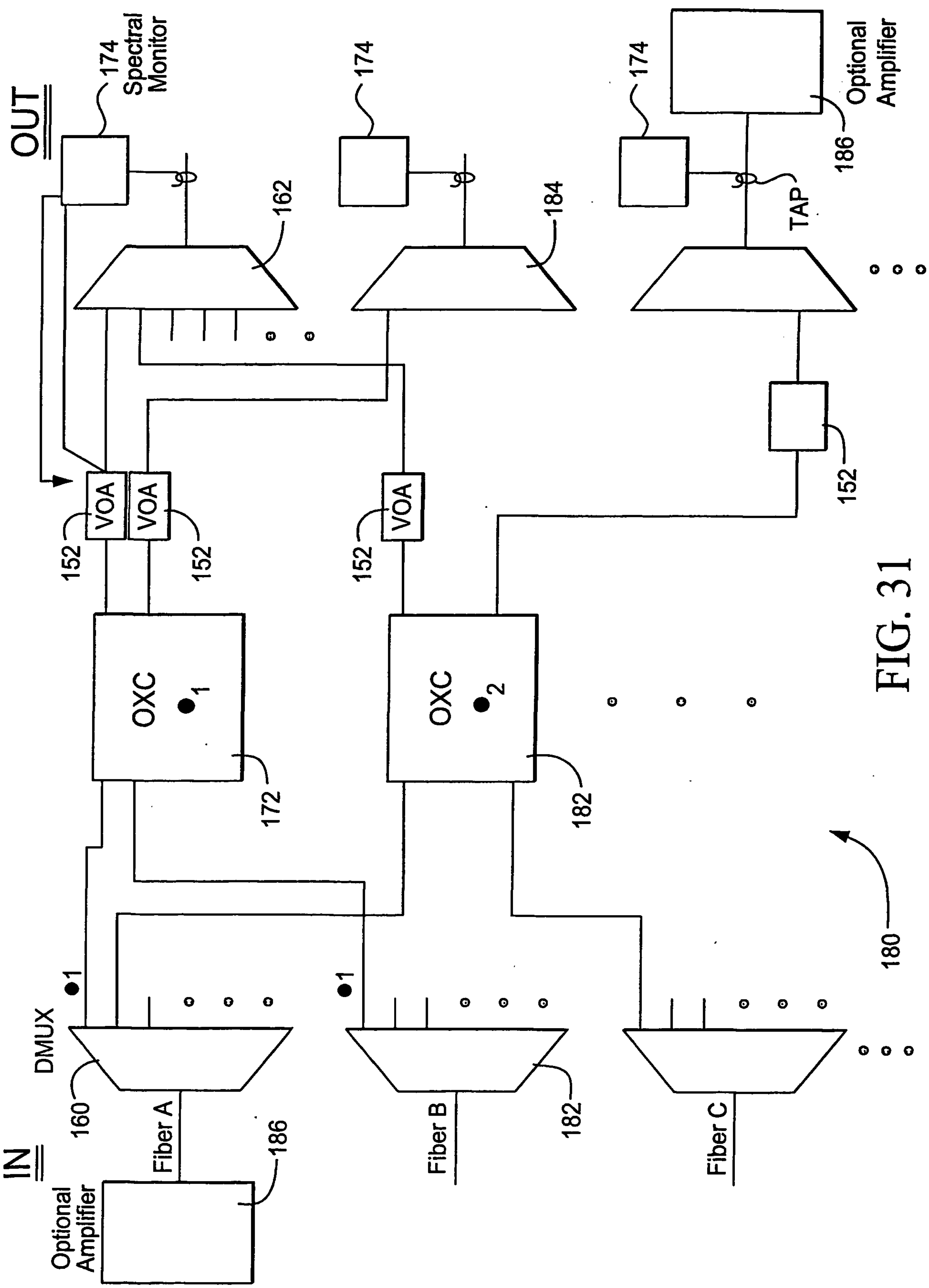
OUT
174
Spectral Monitor
174
174
Optional Amplifier
186
162
184
TAP
VOA
VOA
VOA
152
152
152
152
OXC
1
OXC
2
172
182
180
DMUX
160
182
186
IN
Optional Amplifier
Fiber A
Fiber B
Fiber C

FIG. 31

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
29 November 2001 (29.11.2001)

PCT

(10) International Publication Number
WO 01/091349 A3

(51) International Patent Classification⁷: H04Q 11/00, H04J 14/02, G02F 1/125, 1/01

(21) International Application Number: PCT/US01/15949

(22) International Filing Date: 15 May 2001 (15.05.2001)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/206,767 23 May 2000 (23.05.2000) US
09/666,210 21 September 2000 (21.09.2000) US

(63) Related by continuation (CON) or continuation-in-part (CIP) to earlier applications:
US 60/206,767 (CIP)
Filed on 23 May 2000 (23.05.2000)
US 09/666,210 (CIP)
Filed on 21 September 2000 (21.09.2000)

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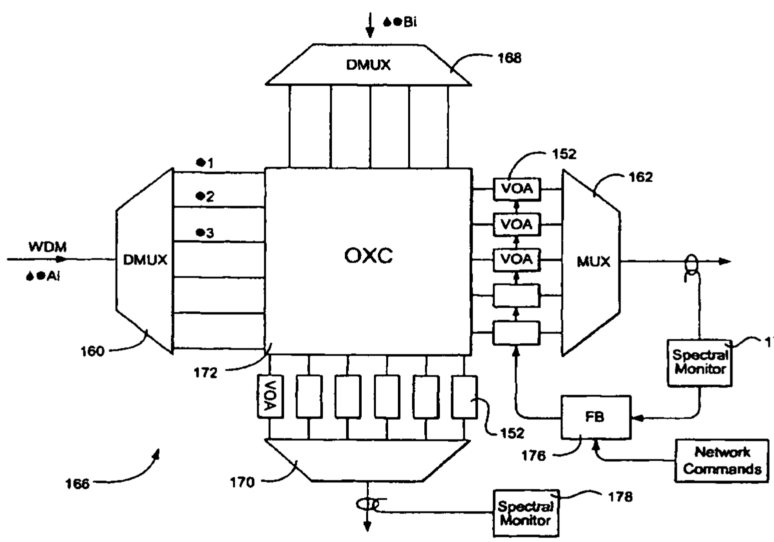
(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE,

[Continued on next page]

(54) Title: CHANNEL EQUALIZER WITH ACOUSTO-OPTIC VARIABLE ATTENUATORS



(57) Abstract: An optical communication assembly has an optical cross connect coupled to a first, a second, a third and a fourth set of optical fibers. A first demultiplexer (160) is coupled to a first input fiber and the first set of optical fibers and a second demultiplexer (168) is coupled to a second input fiber and the second set of optical fibers. A first multiplexer (162) is coupled to a first output fiber and the third set of optical fibers. A second multiplexer (170) is coupled to a second output fiber and the fourth set of optical fibers. A first set of attenuators (152) is coupled to the third set of optical fibers and a second set of attenuators(152) coupled to the fourth set of optical fibers. The attenuators may consist of acousto-optic tunable filters and are controlled by an electronic feedback loop.

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IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published:
- *with international search report*
- *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

(88) Date of publication of the international search report: 12 September 2002

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 01/15949

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H04Q11/00 H04J14/02 G02F1/125 G02F1/01

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H04Q G02F H04J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

WPI Data, PAJ, IBM-TDB, EPO-Internal, INSPEC, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 959 579 A (NORTEL NETWORKS CORP) 24 November 1999 (1999-11-24)	1
A	column 5, line 31 -column 6, line 27	2-14, 26-39, 51-61
	column 8, line 19 - line 32 column 9, line 42 -column 10, line 10; figures 2,4	

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier document but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
22 May 2002	05/07/2002

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Stang, I

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 01/15949

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	VODHANEL R S ET AL: "Network operations and management issues for transparent WDM networks" LASERS AND ELECTRO-OPTICS SOCIETY ANNUAL MEETING, 1994. LEOS '94 CONFERENCE PROCEEDINGS. IEEE BOSTON, MA, USA 31 OCT.-3 NOV. 1994, NEW YORK, NY, USA,IEEE, US, 31 October 1994 (1994-10-31), pages 365-366, XP010220823 ISBN: 0-7803-1470-0 page 365, right-hand column, paragraph 1; figure 2	51,53-60
A	US 5 970 201 A (ANTHONY PHILIP JOHN ET AL) 19 October 1999 (1999-10-19) column 4, line 8 -column 5, line 55 column 1, line 30 - line 33; figure 3	1-8,12, 14,15, 26-36, 40,51, 54-61
A	HYO SANG KIM ET AL: "ACTIVELY GAIN-FLATTENED ERBIUM-DOPED FIBER AMPLIFIER OVER 35 NM BY USING ALL-FIBER ACOUSTOOPTIC TUNABLE FILTERS" IEEE PHOTONICS TECHNOLOGY LETTERS, IEEE INC. NEW YORK, US, vol. 10, no. 6, 1 June 1998 (1998-06-01), pages 790-792, XP000755469 ISSN: 1041-1135 page 790, right-hand column -page 791, left-hand column, paragraph 1; figure 1	15-25, 40-71
A	PATENT ABSTRACTS OF JAPAN vol. 1999, no. 10, 31 August 1999 (1999-08-31) -& JP 11 127121 A (FUJITSU LTD), 11 May 1999 (1999-05-11) abstract	51-60
E	-& US 6 278 536 B1 (KAI ET AL.) 21 August 2001 (2001-08-21) column 20, line 5 - line 48 column 21, line 1 - line 9 column 21, line 66 -column 22, line 33; figures 2-4	51-60

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 01/15949

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